# Overview of plasma wave studies using the Basic Plasma Science Facility

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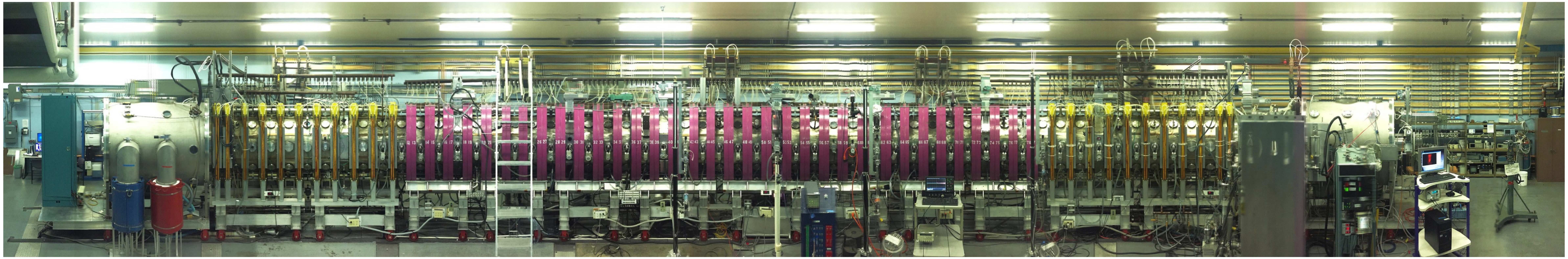
PSTI UCLA
Plasma Science and Technology Institute

UCLA

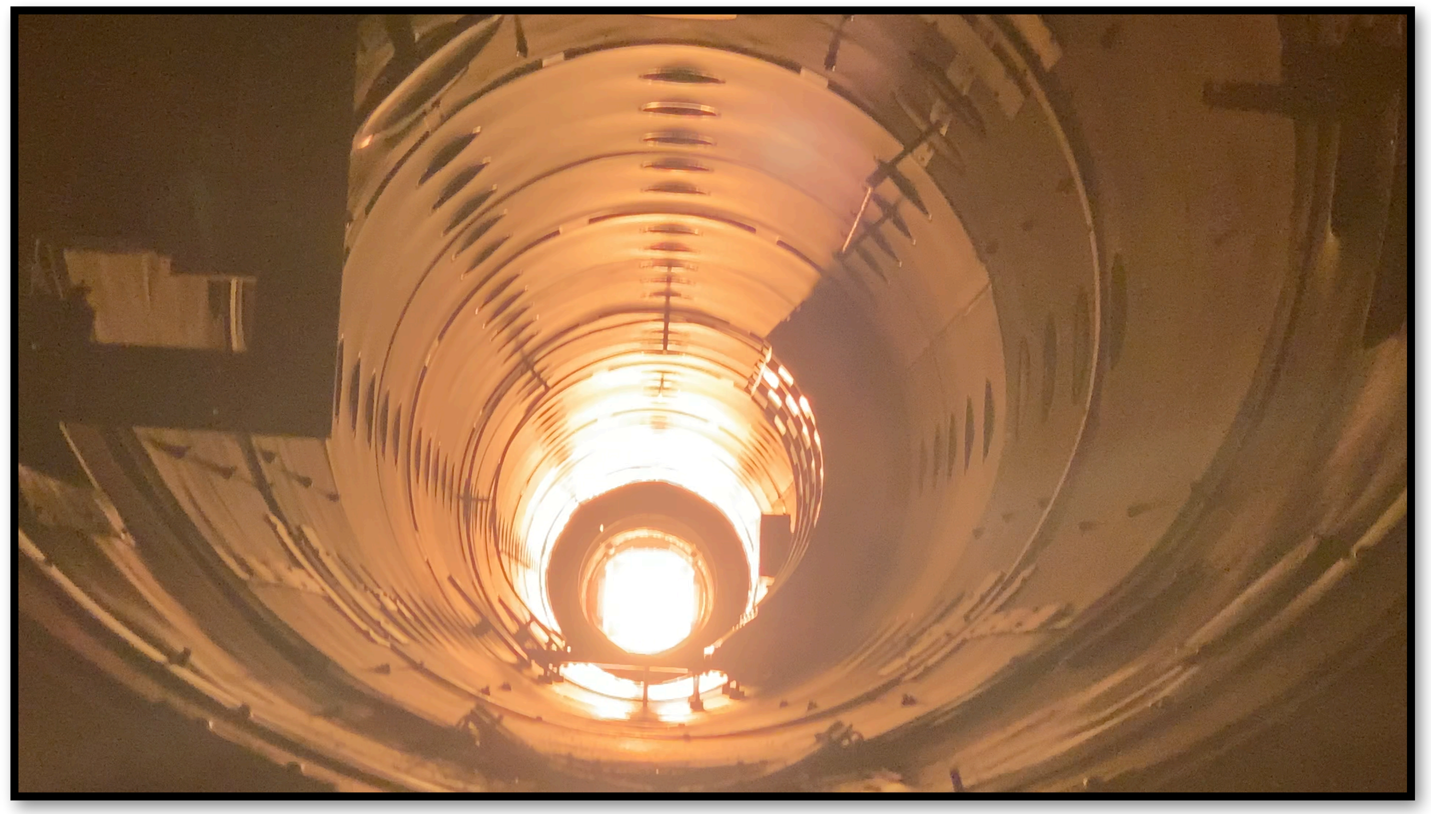
# Summary

- Basic Plasma Science Facility: US DOE and NSF sponsored user facility for study of fundamental processes in magnetized plasmas. Primary device is Large Plasma Device (LAPD).
- Wide range of studies performed: waves, instabilities, turbulence & transport, shocks, reconnection. Brief highlights of recent experiments will be given, with a longer discussion on Alfvén wave studies, including
  - the first observation of a parametric instability of kinetic Alfvén waves in the laboratory [Dorfman & Carter PRL 2016]
  - high power fast wave excitation in LAPD (ICRF): Measurements of RF rectified sheaths on antenna structure [Martin et al., PRL 2017] and parasitic coupling to slow mode

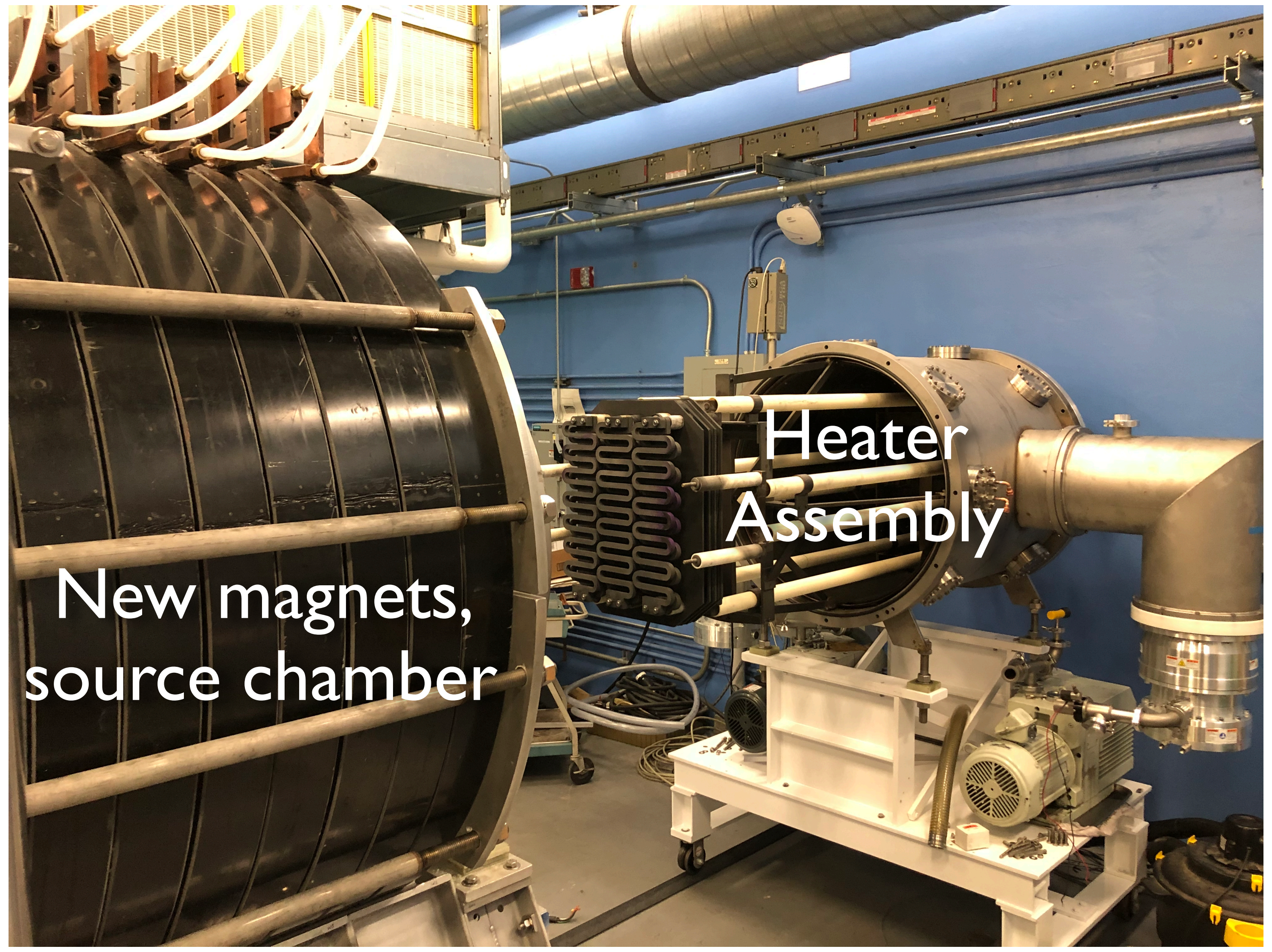
# The LArge Plasma Device (LAPD): a flexible experimental platform

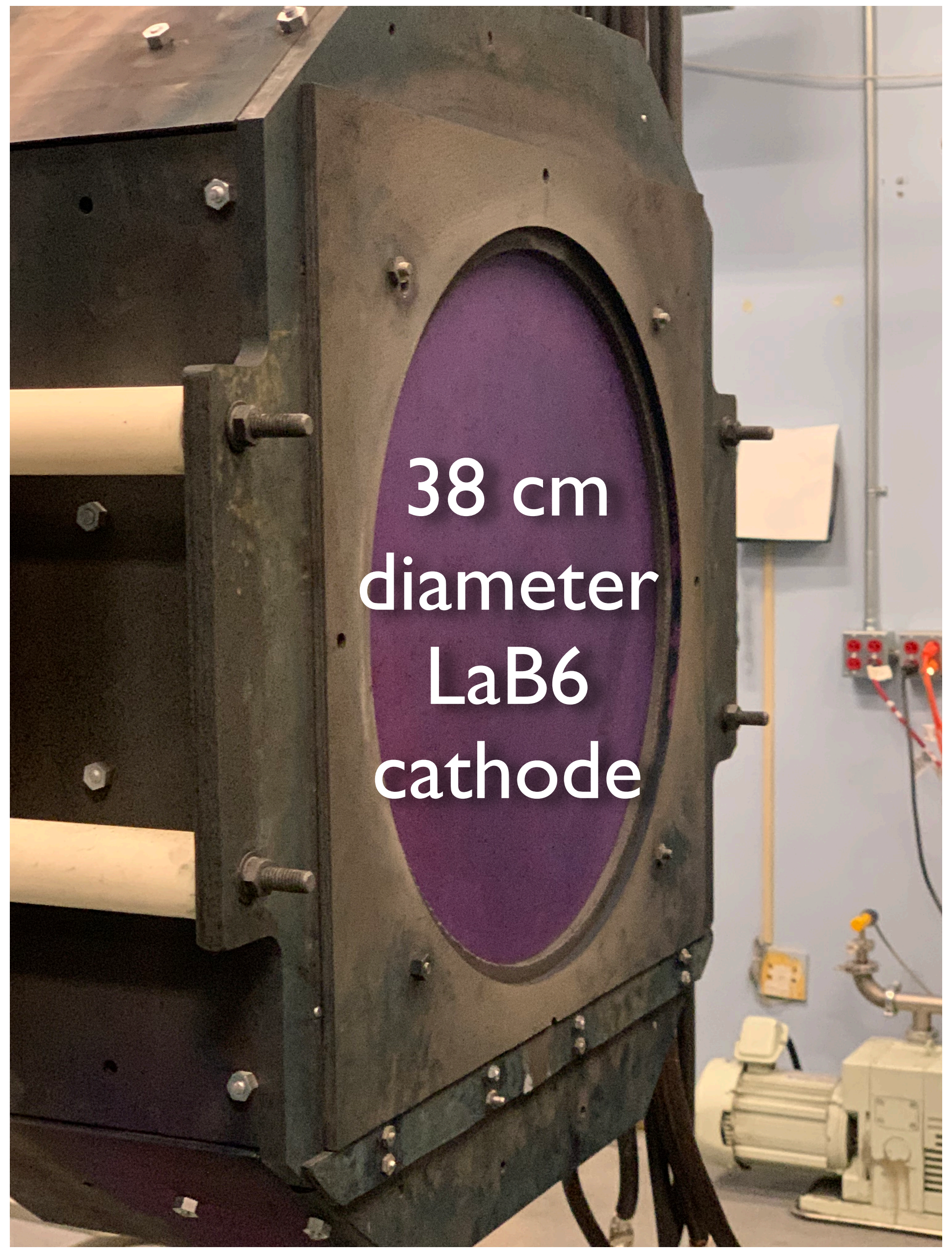


- 20m long, 1m diameter vacuum chamber; emissive cathode discharge
- $LaB_6$ Cathode: n ~ $5 \times 10^{13}$ $cm^{-3}$, $T_e$ ~ 10-15 eV, $T_i$ ~ 6-10 eV
- B up to 2.5kG (with control of axial field profile)
- High repetition rate:  1 Hz
- US NSF/DOE Sponsored user facility, international users welcome!(**proposals will be due Dec 2021**)



# Major Plasma Source Upgrade: large-area $LaB_6$



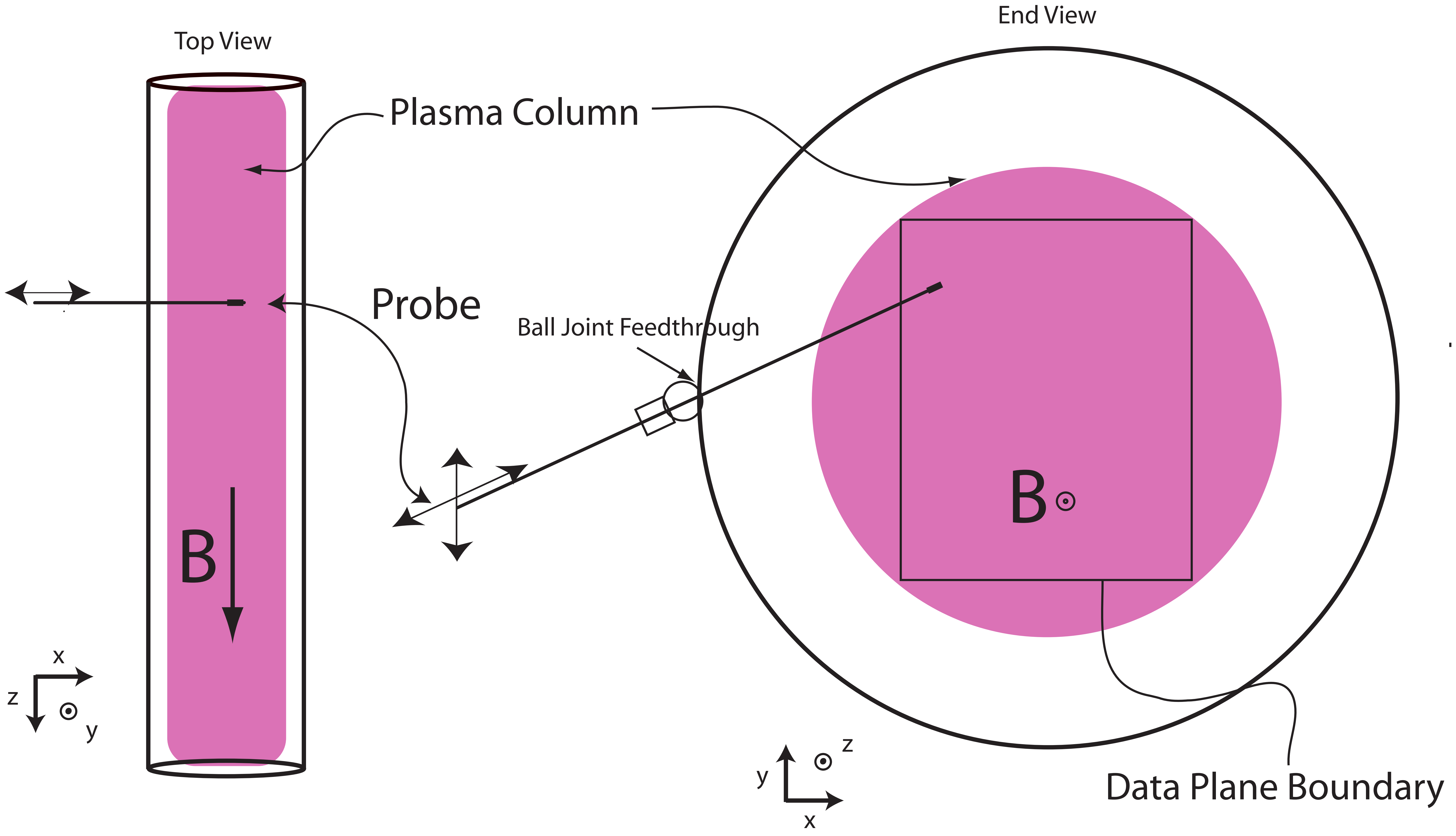

- New large-area $LaB_6$ emissive cathode source provides higher power density, access to higher density, higher pressure → magnetized plasma at higher $\beta$ (currently at 0.2 reliable plasmas)

- Design, fabrication and installation complete in spite of COVID-19 delays and restrictions

- Facility has restarted research operations and hosting external users

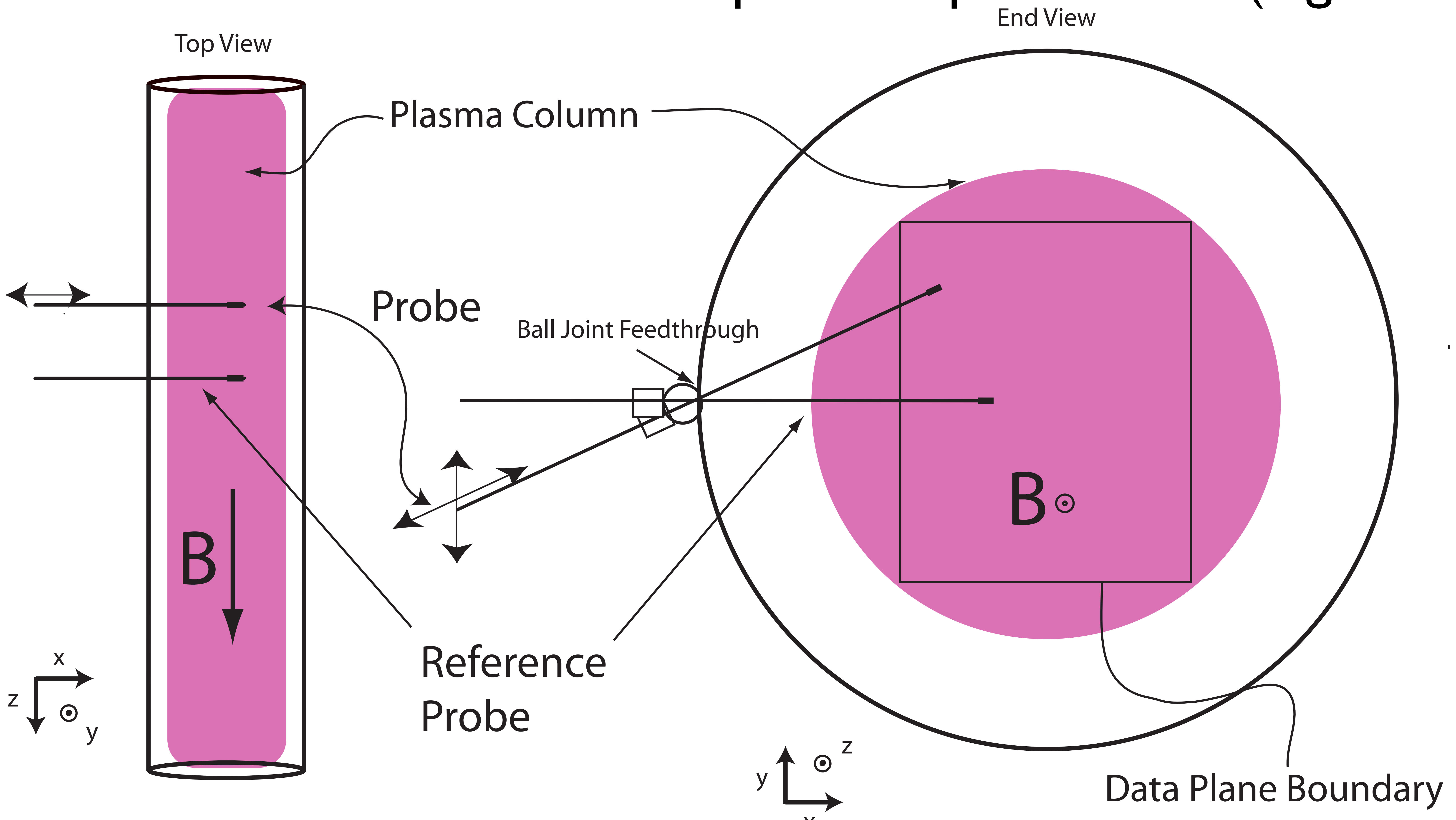
# Measurement methodology in LAPD

- Use single probes to measure local density, temperature, potential, magnetic field, flow: move single probe shot-to-shot to construct average profiles

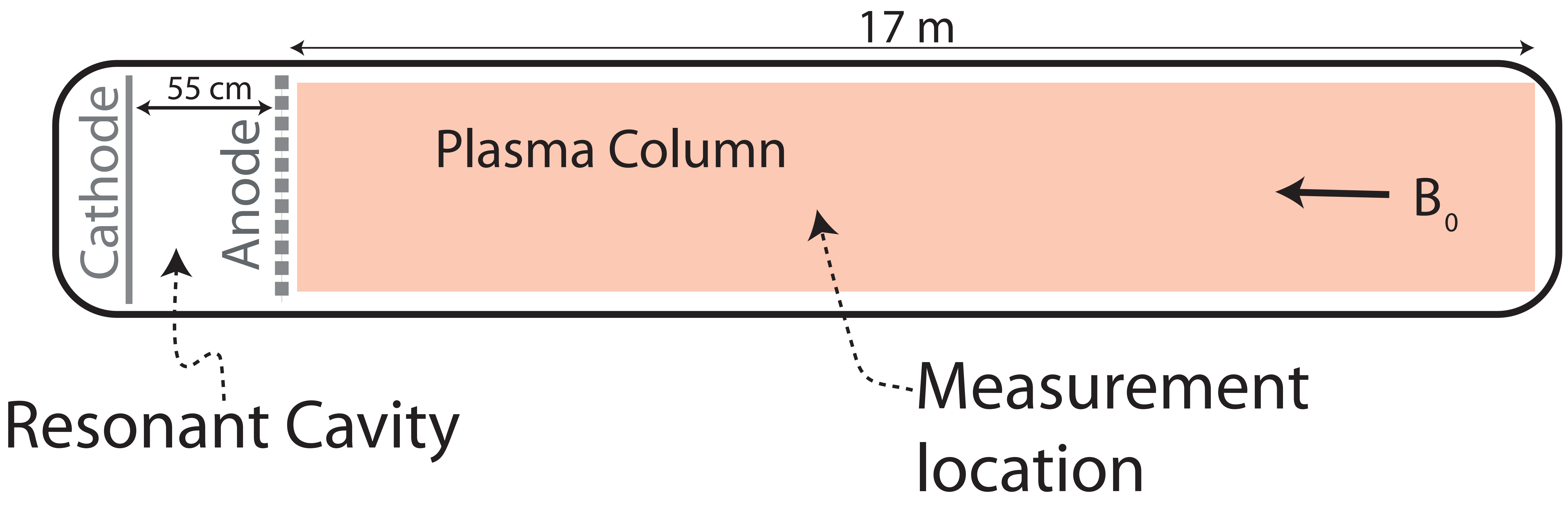


# Measurement methodology in LAPD

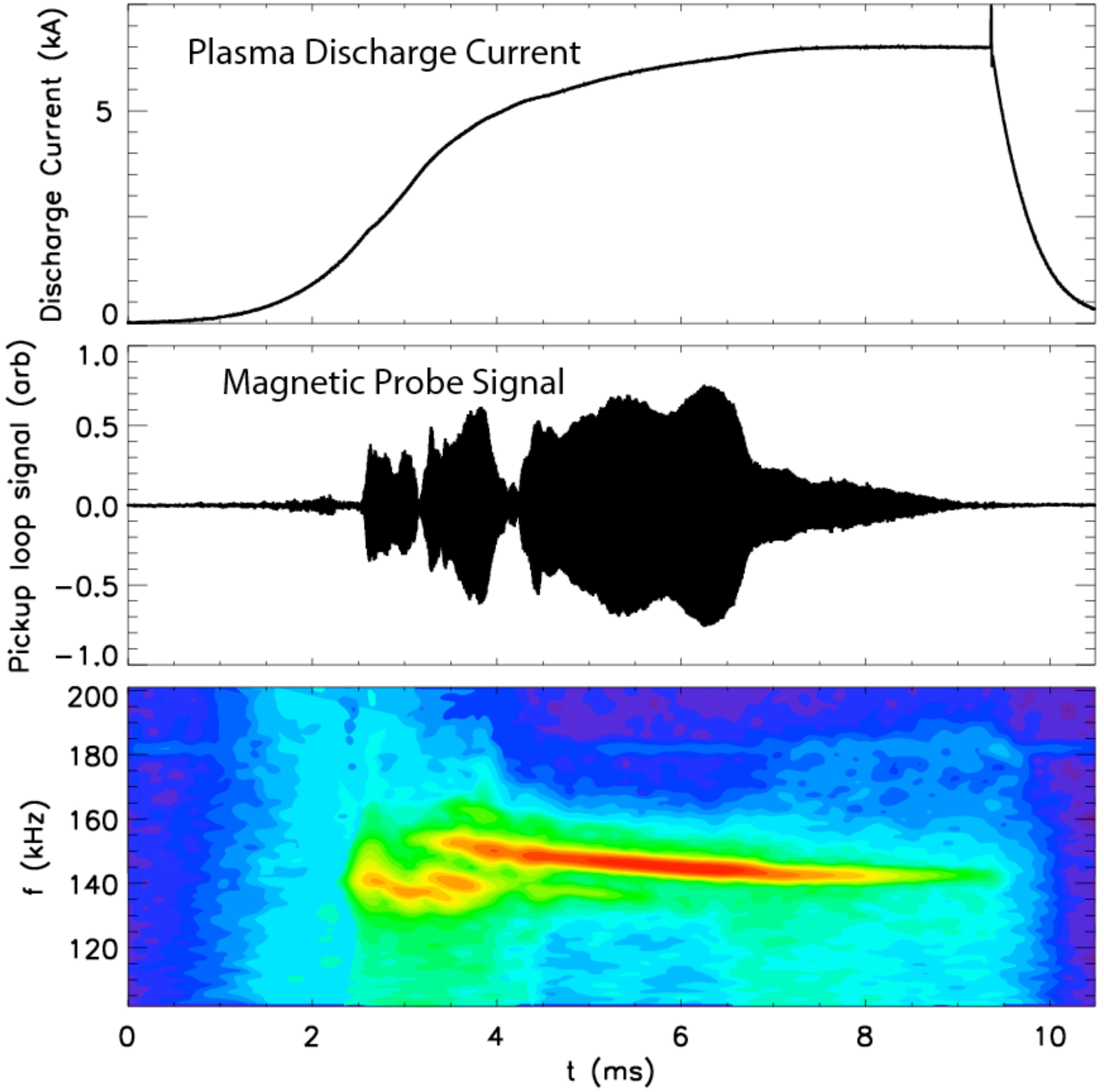
- Use single probes to measure local density, temperature, potential, magnetic field, flow: move single probe shot-to-shot to construct average profiles
- Add a second (reference) probe to use correlation techniques to make detailed statistical measurements of non-repeatable phenomena (e.g. turbulence)



# Example data: Alfvén wave MASER

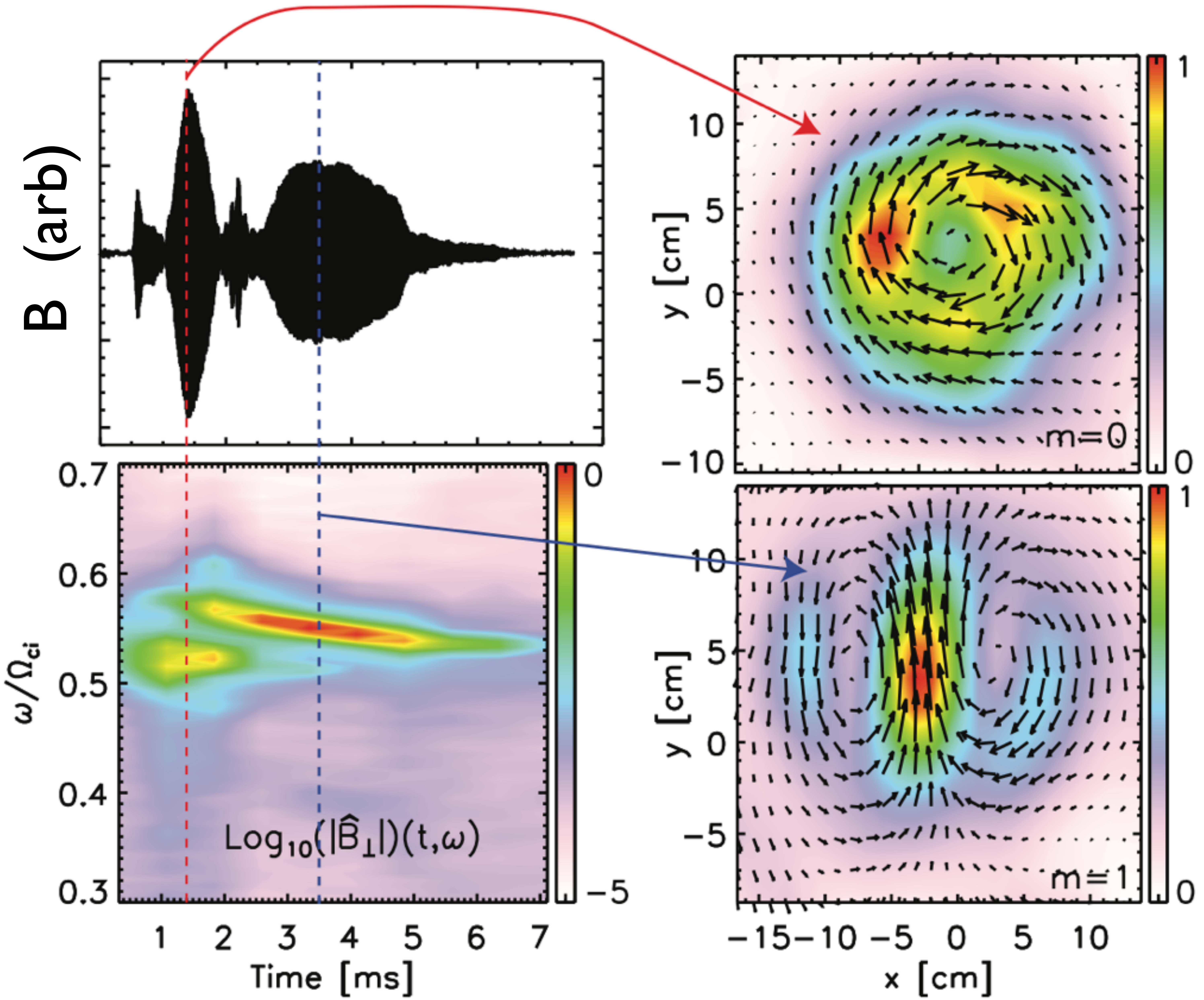


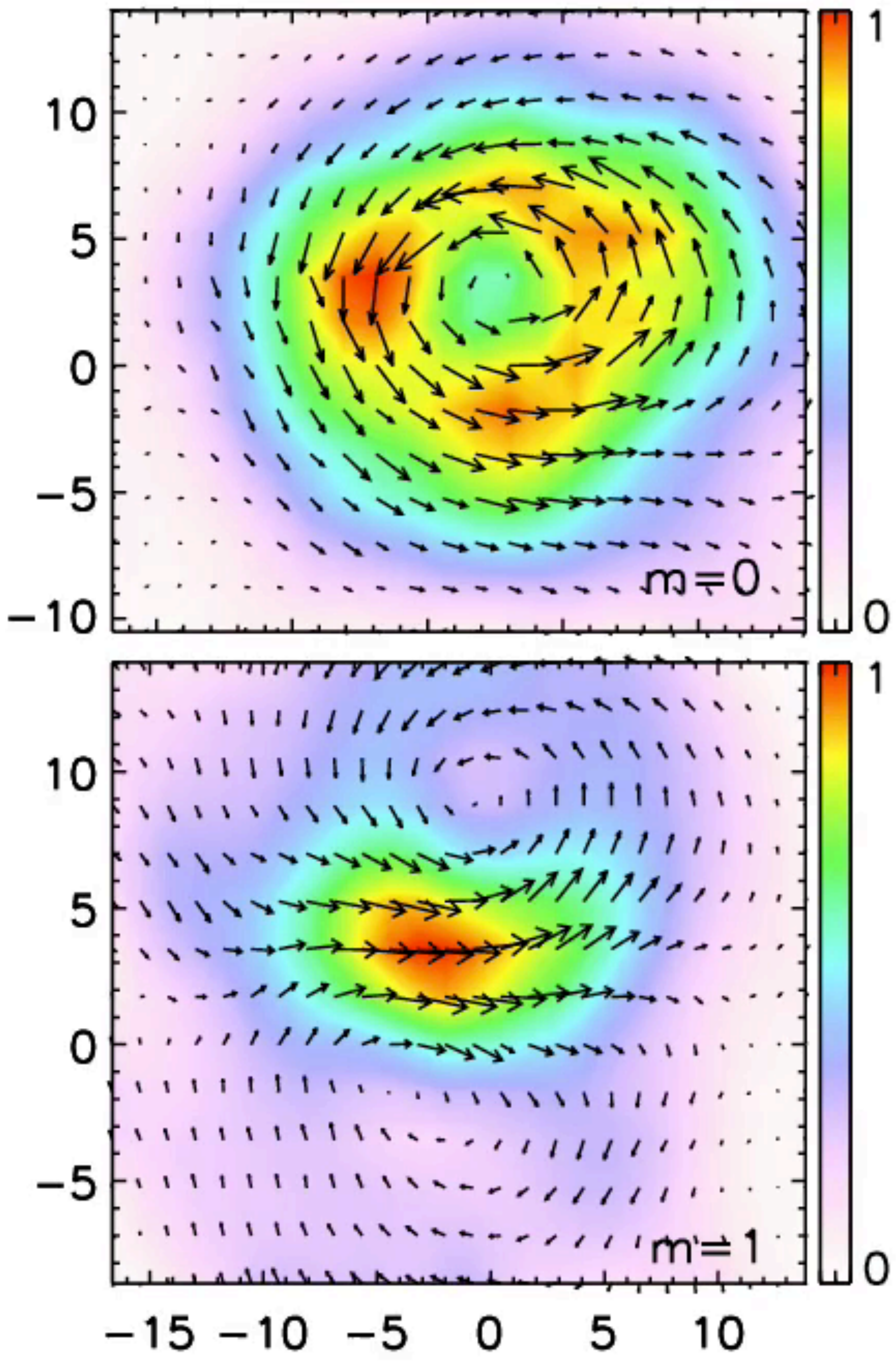

- Plasma source acts as resonant cavity for shear Alfvén waves
- Driven spontaneously by discharge current (thought to be inverse Landau damping on return current electrons)
- Alfvén wave "MASER"




Maggs, Morales, PRL 91, 035004 (2003)
Maggs, Morales, Carter, PoP 12, 013103 (2005)

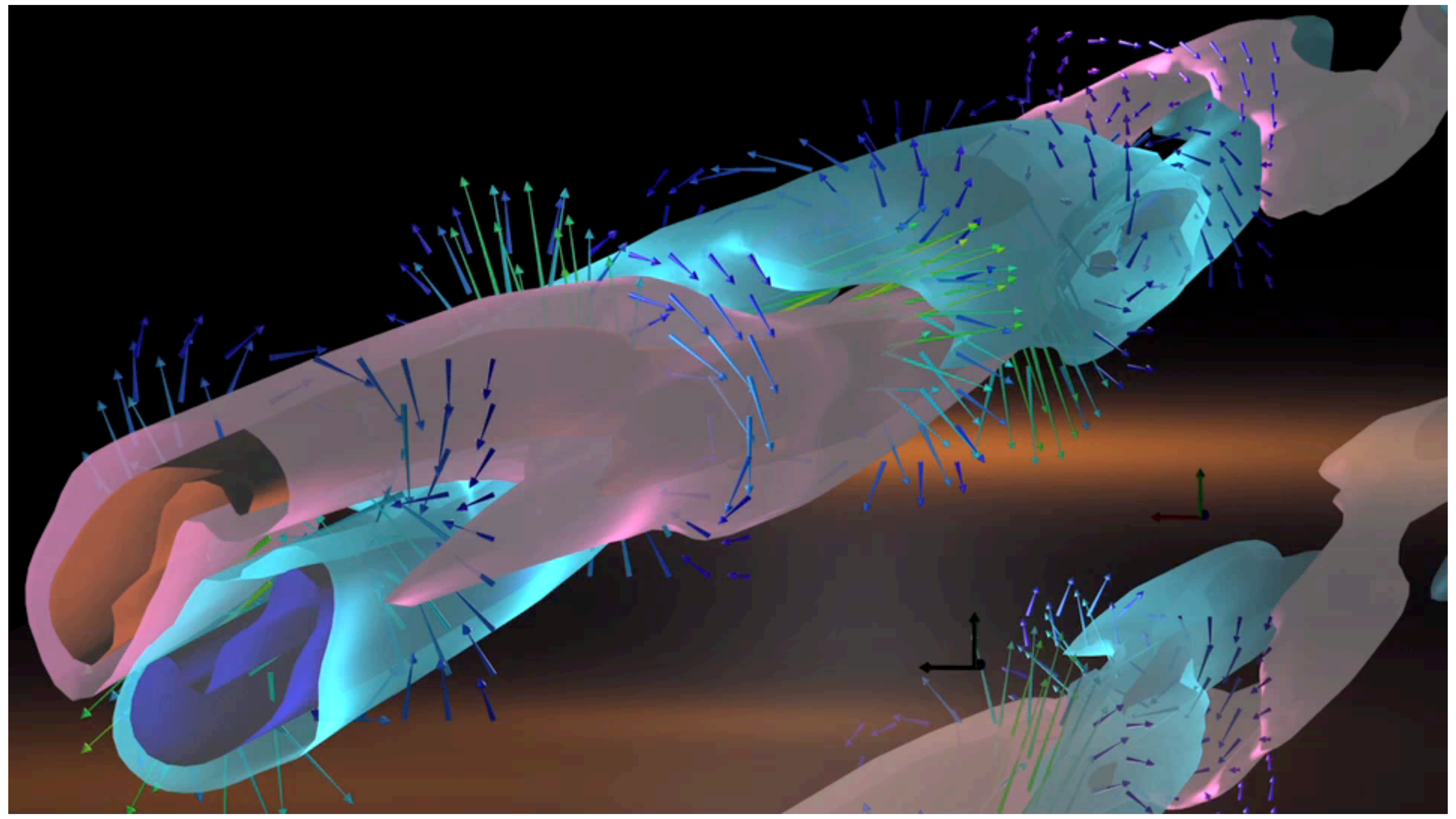
# Measured structure of Alfvén eigenmodes in LAPD

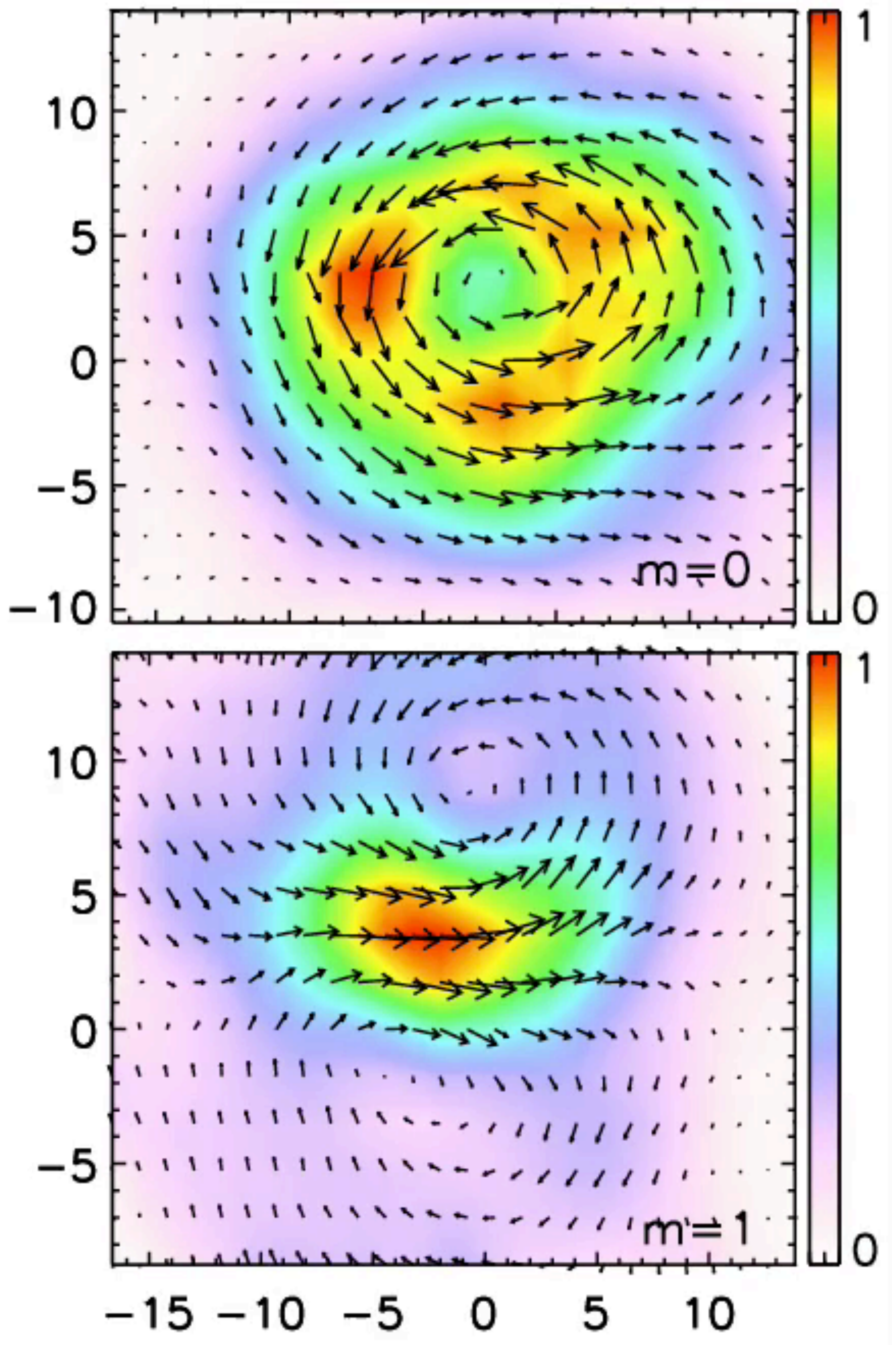



m=0
m=1

# Extensive studies of Alfvén wave physics in LAPD

- LAPD created to enable AW research need length to fit parallel wavelength (~few meters)
- Measured pattern of wave current and magnetic field from a LHP kinetic shear Alfvén wave in LAPD; measured pattern of m=0, m=1 cylindrical AEs in LAPD



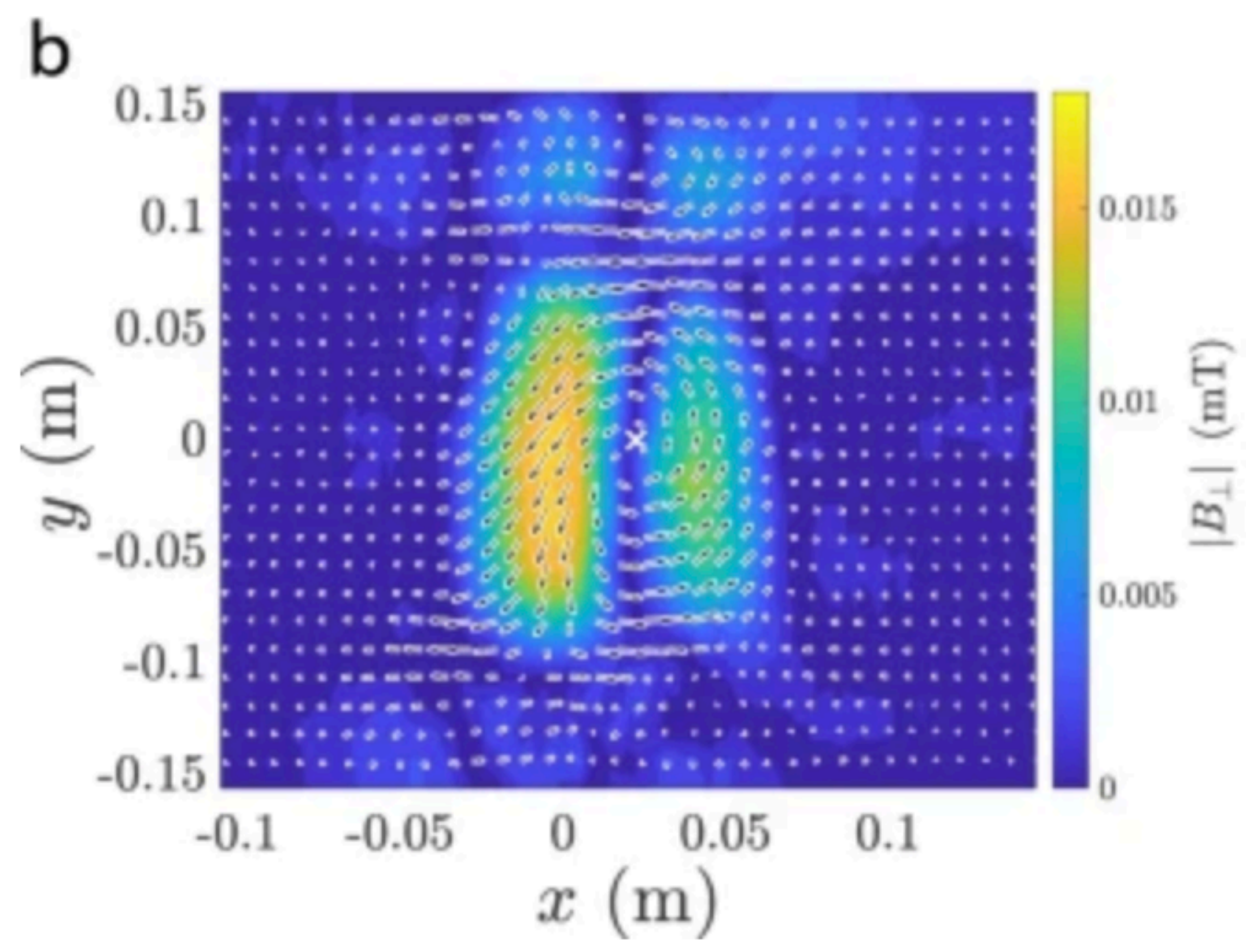


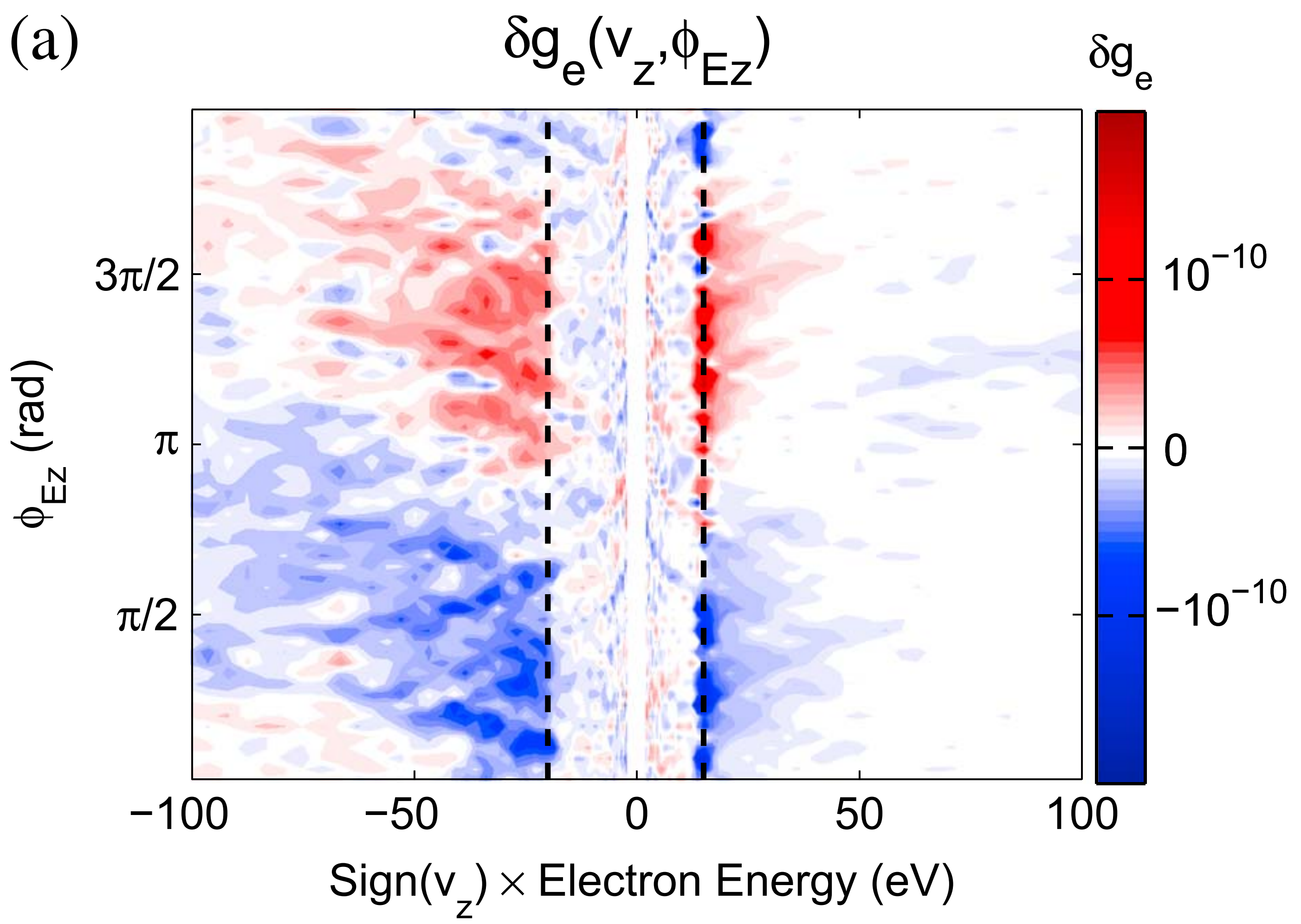

- A number of issues studied over the years: radiation from small source, resonance cones, field line resonances, wave reflection, conversion from KAW to IAW on density gradient…

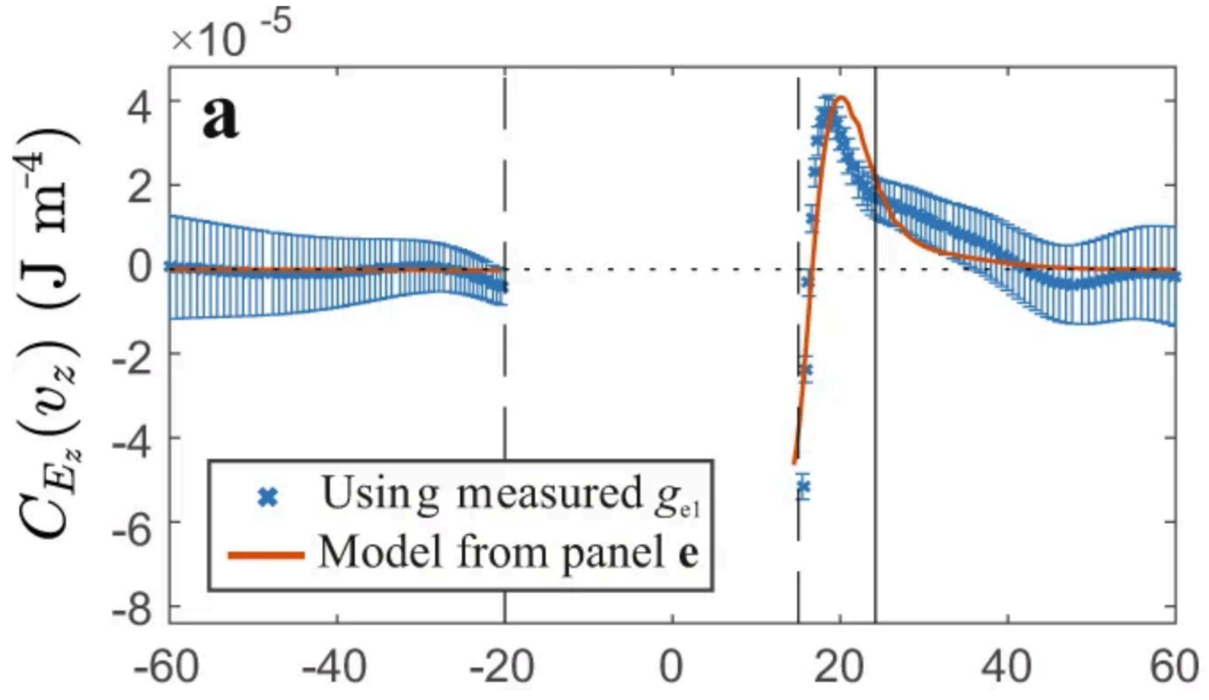
Review: Gekelman, et al., PoP 18, 055501, (2011)

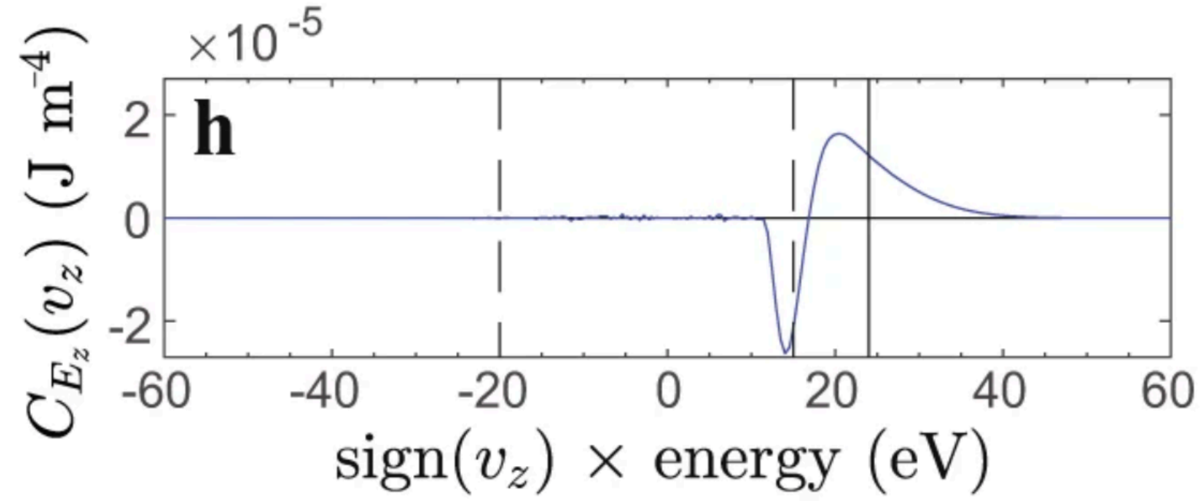
Details, publication list at http://plasma.physics.ucla.edu

# Electron acceleration by inertial Alfvén waves




- Kletzing/Skiff/Howes/Schroeder (Iowa): interest in understanding electron acceleration by Alfvén waves; relevance to generation of Aurora
- Used novel electron distribution diagnostic (whistler wave absorption (Skiff)) to demonstrate acceleration of electrons by inertial Alfvén waves

Schroeder, et al., Nature Comm. 12, 3103 (2021)

# Electron acceleration by inertial Alfvén waves

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## The mysterious origin of the northern lights has been proven

By Jennifer Gray, CNN meteorologist
Updated 2:32 PM ET, Tue June 8, 2021

physicsworld Maga

plasma physics

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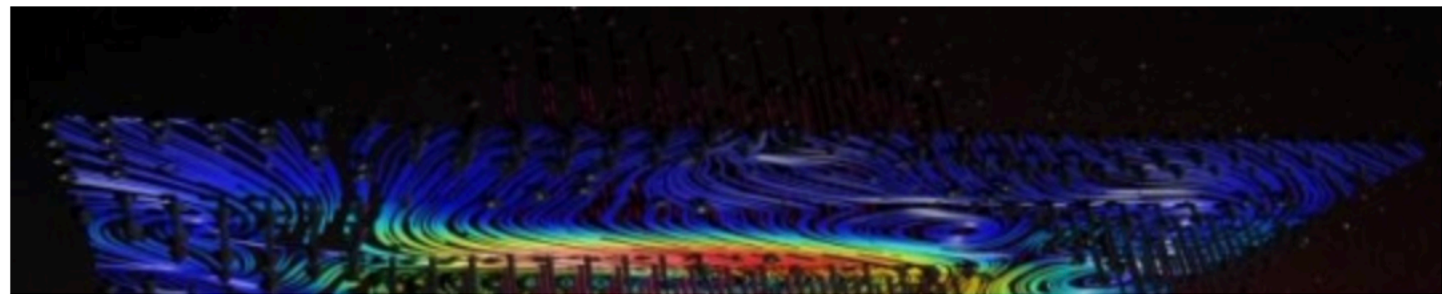
## Electrons 'surf' on Alfvén waves in plasma-chamber experiments

22 Jun 2021



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It took researchers more than 20 years to figure out this light show mystery.

BY RAHUL RAO | PUBLISHED JUN 21, 2021 7:00 PM

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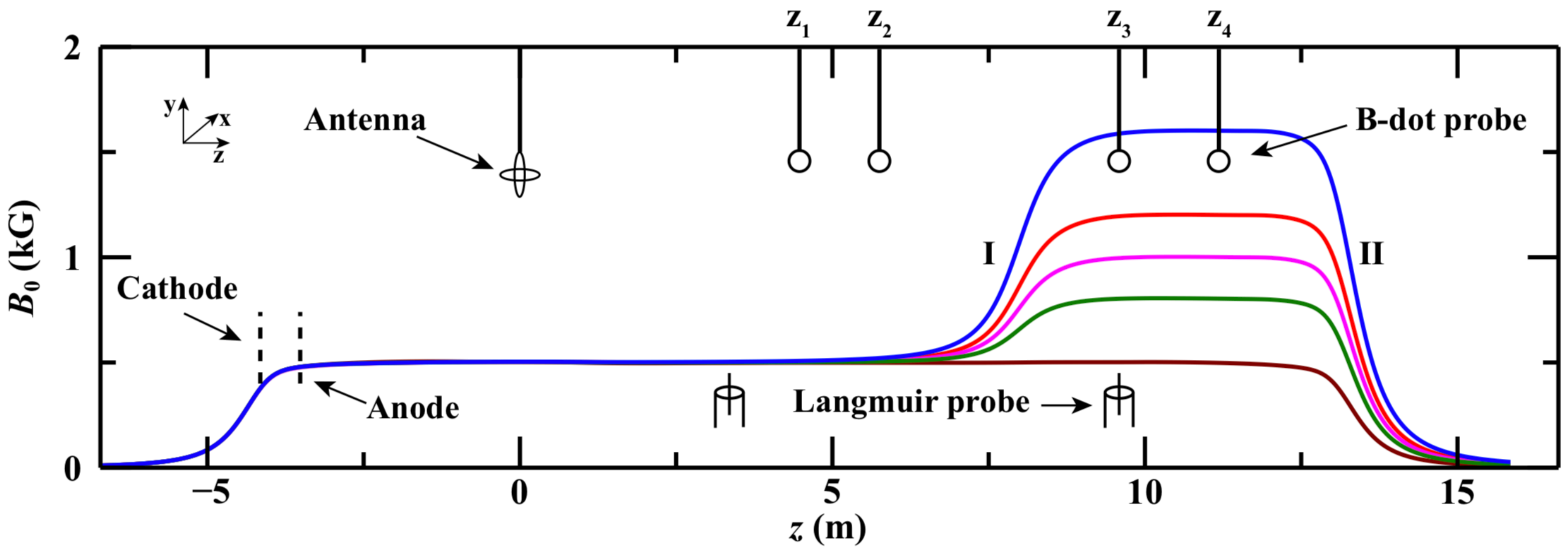
## Auroras form when electrons from space ride waves in Earth's magnetic field

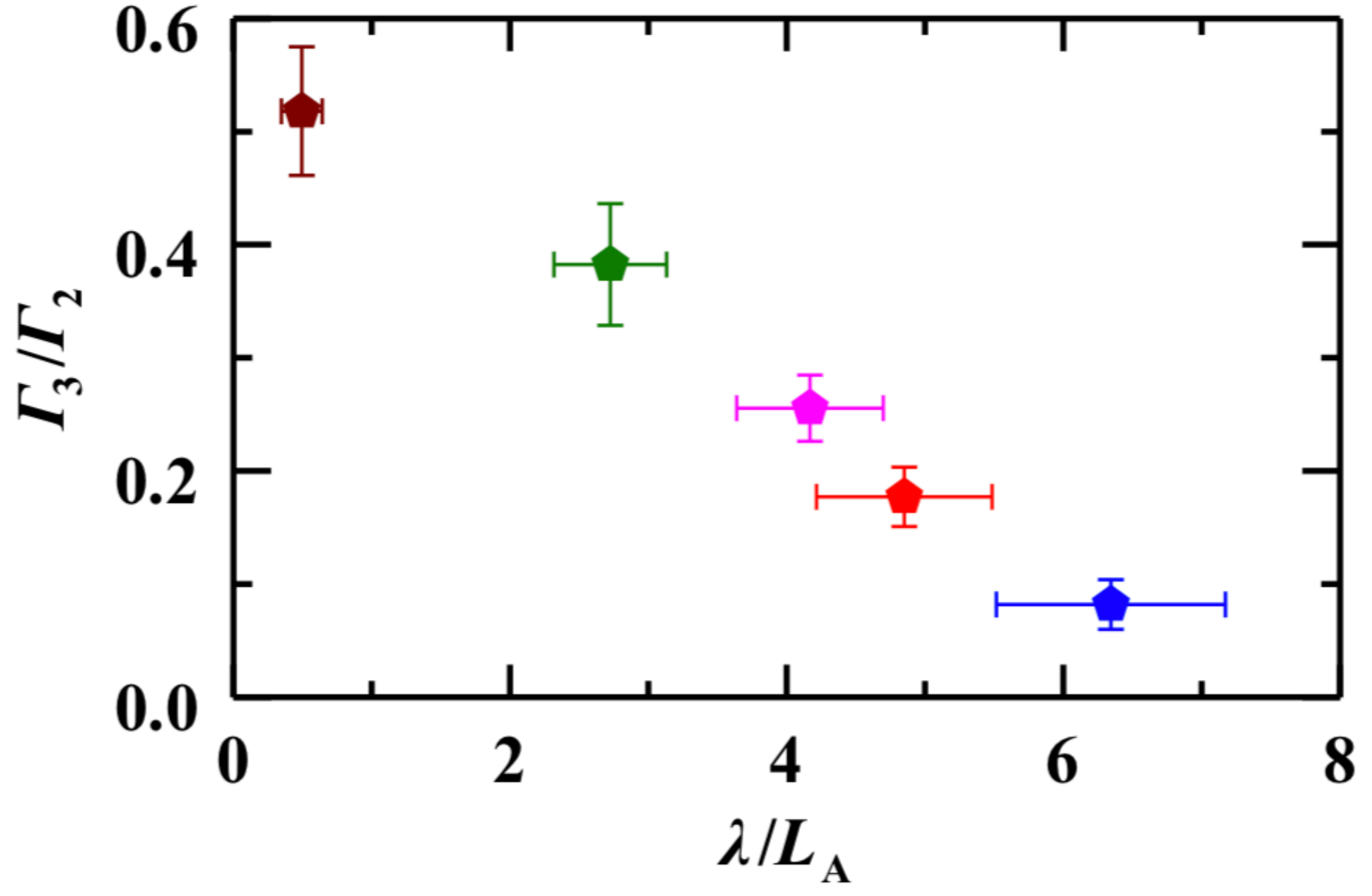
The same physics could give rise to auroras on Jupiter and Saturn

Schroeder, et al., Nature Comm. 12, 3103 (2021)

# Propagation of Alfvén waves in parallel Alfvén speed gradients

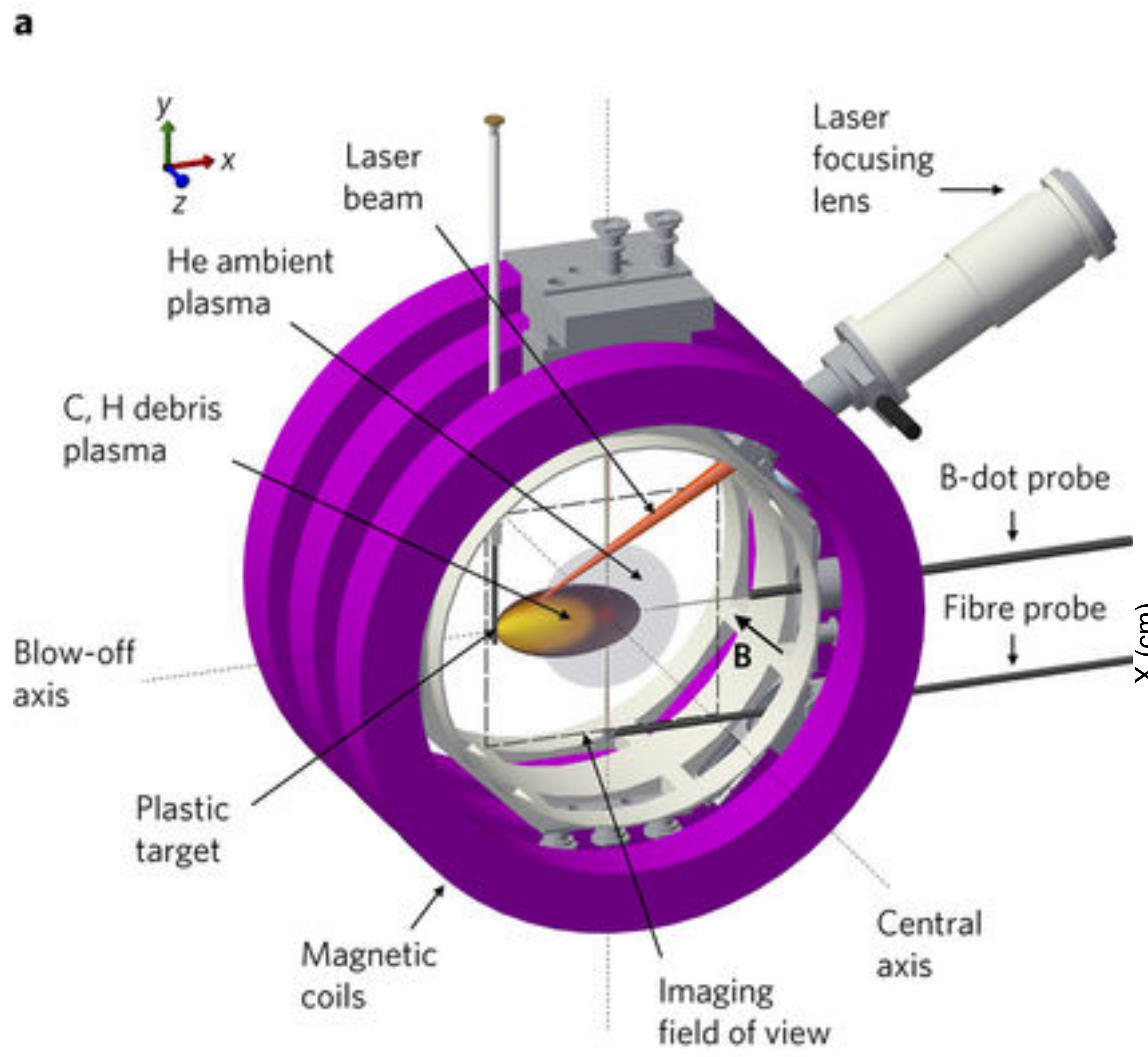



- Savin, Hahn, Bose (Columbia): reflection/absorption of AWs propagating into speed gradient (coronal heating/coronal holes)
- Clear reduction in wave energy with increasing normalized speed gradient, but no sign of wave reflection! Absorption?

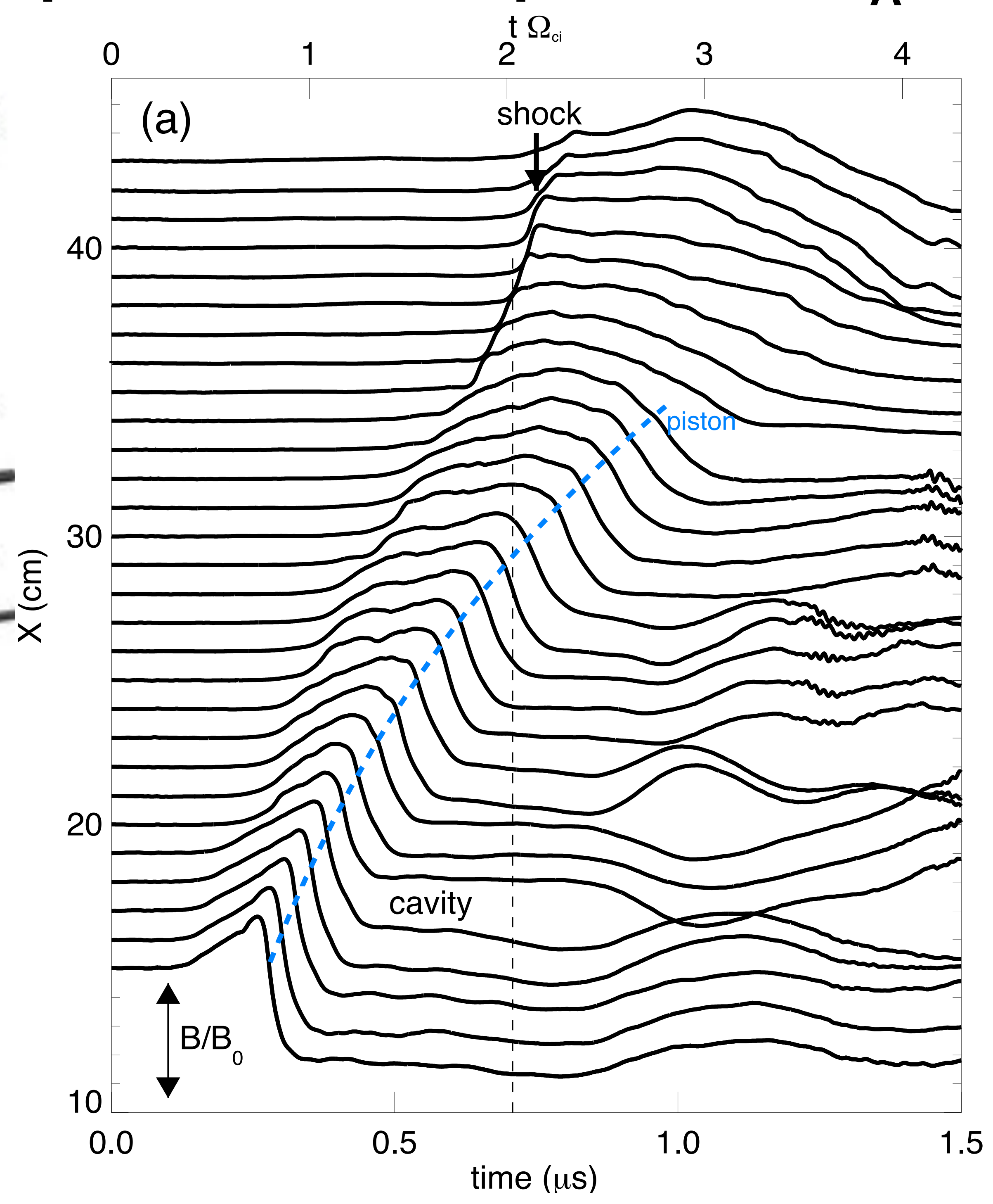


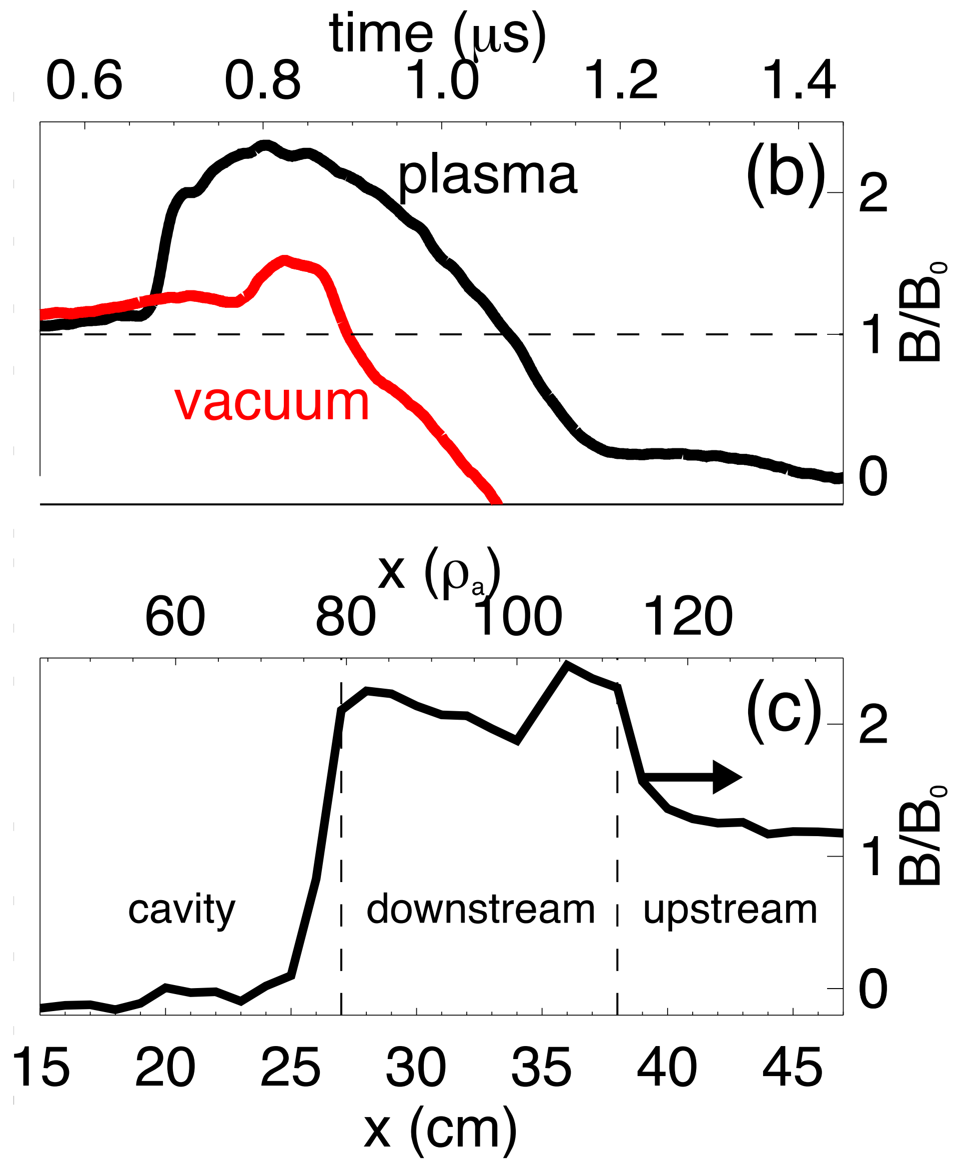

Bose, et al., ApJ 882 183 (2019)

# Creating collisionless shocks in the laboratory




**Magnetic pulse at bubble edge separates from piston and steepens into $M_A$~2 shock**



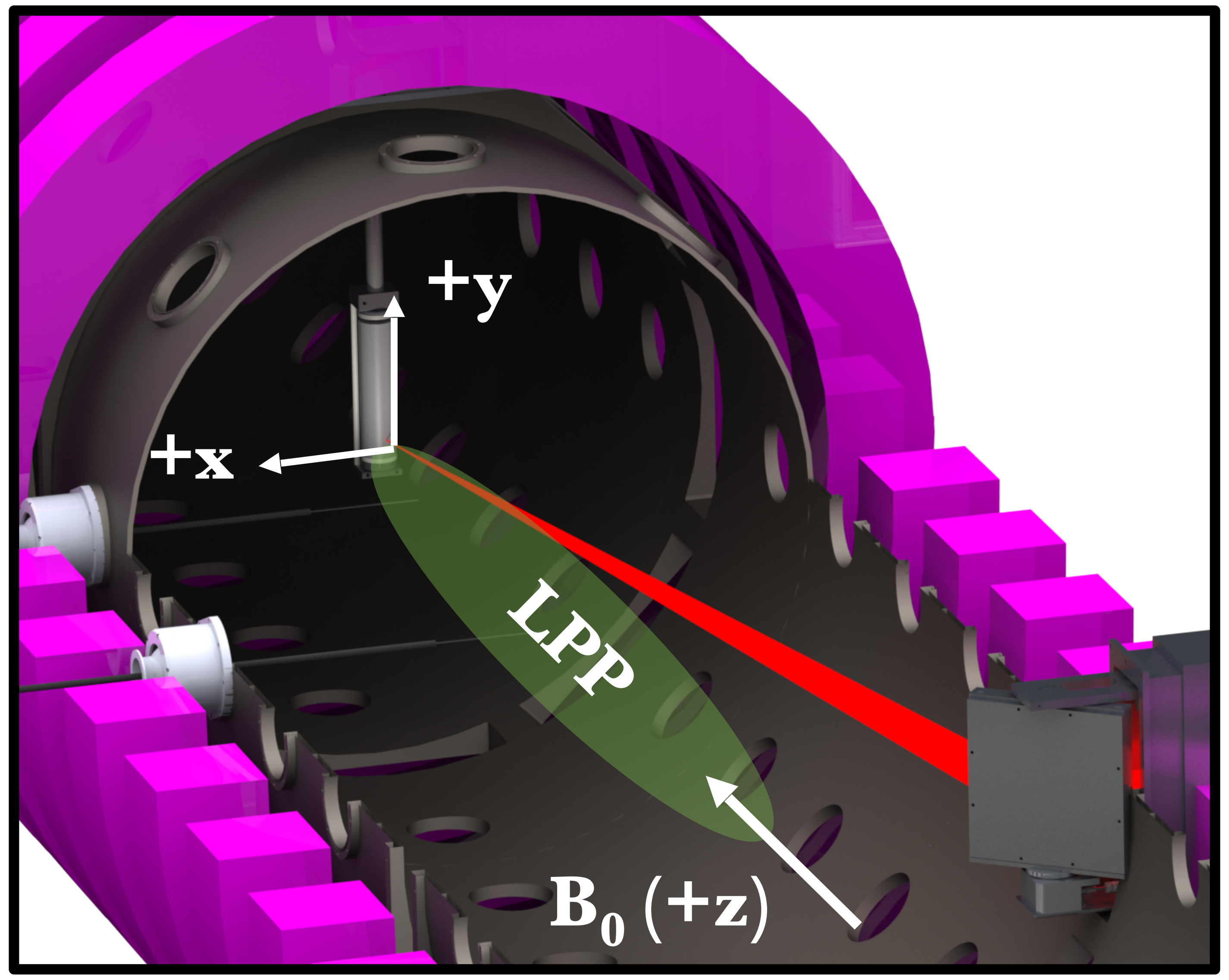



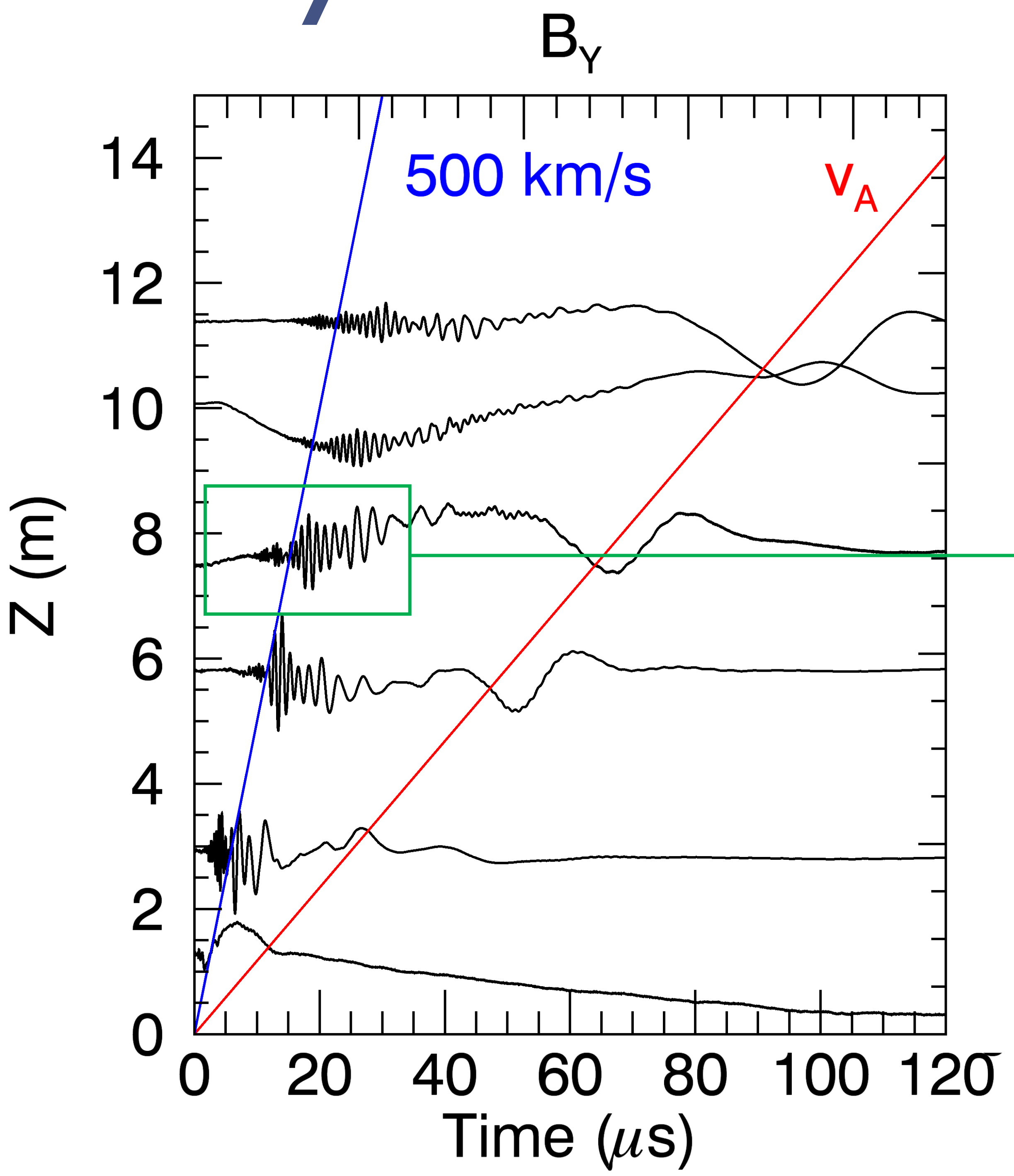


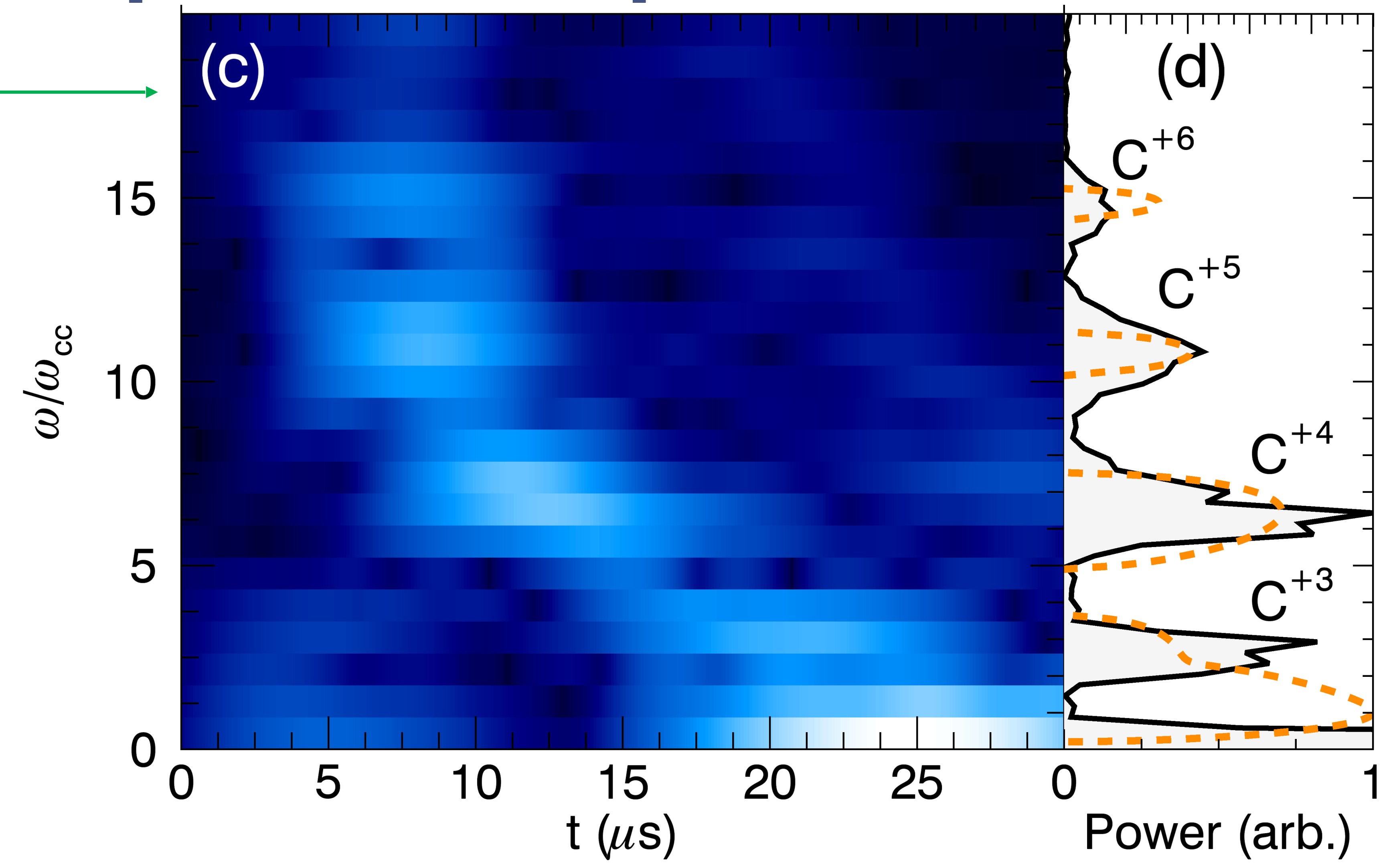
- Quasi-perpendicular collisionless, magnetized shocks created using 200J laser (Niemann, UCLA); consistent with "Larmor Coupling" mechanism

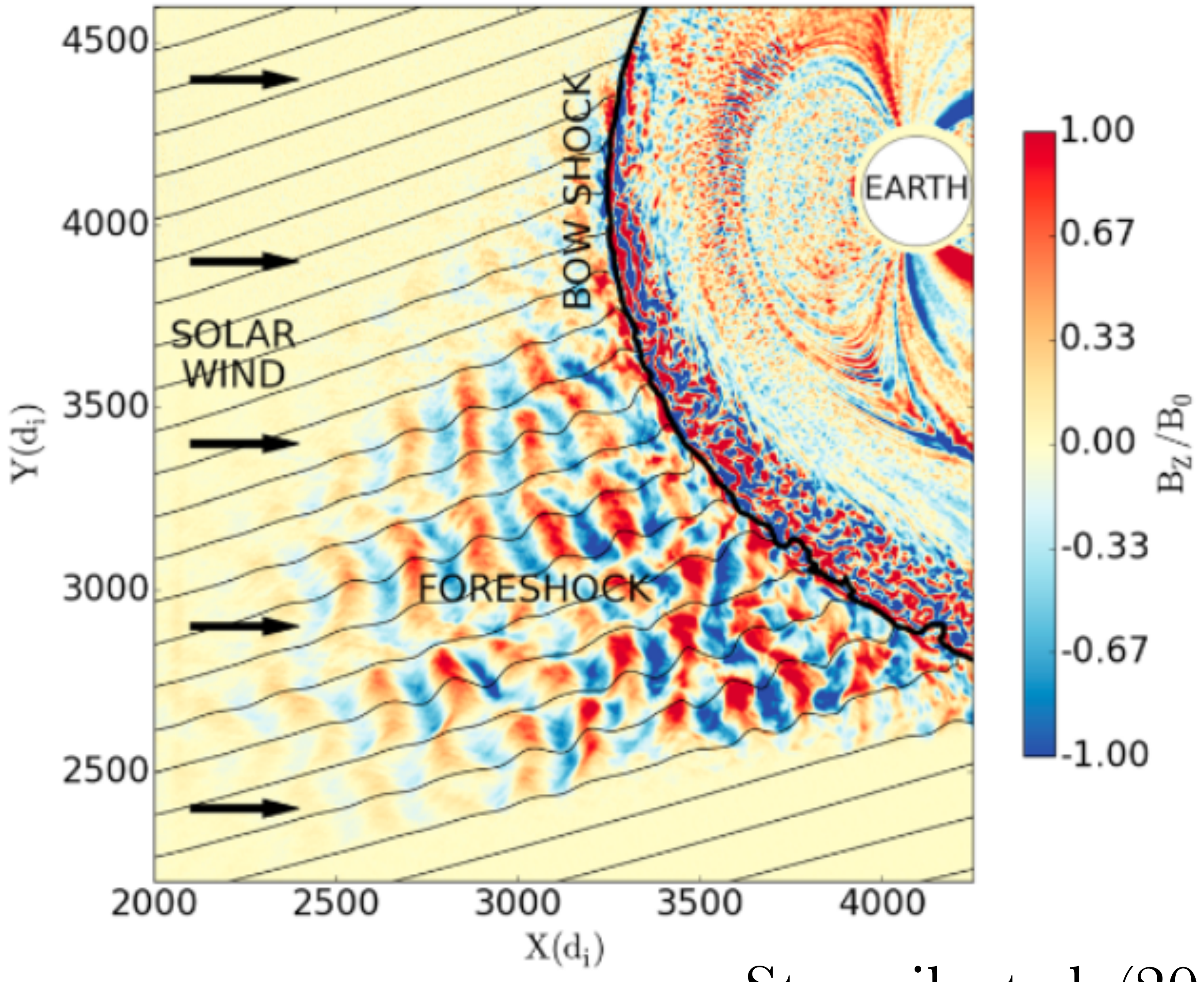
Bondarenko, et al., *Nature Physics* **13**, 573–577 (2017)

# Creating collisionless shocks in the laboratory: Right-hand resonant instability observed with parallel "piston"



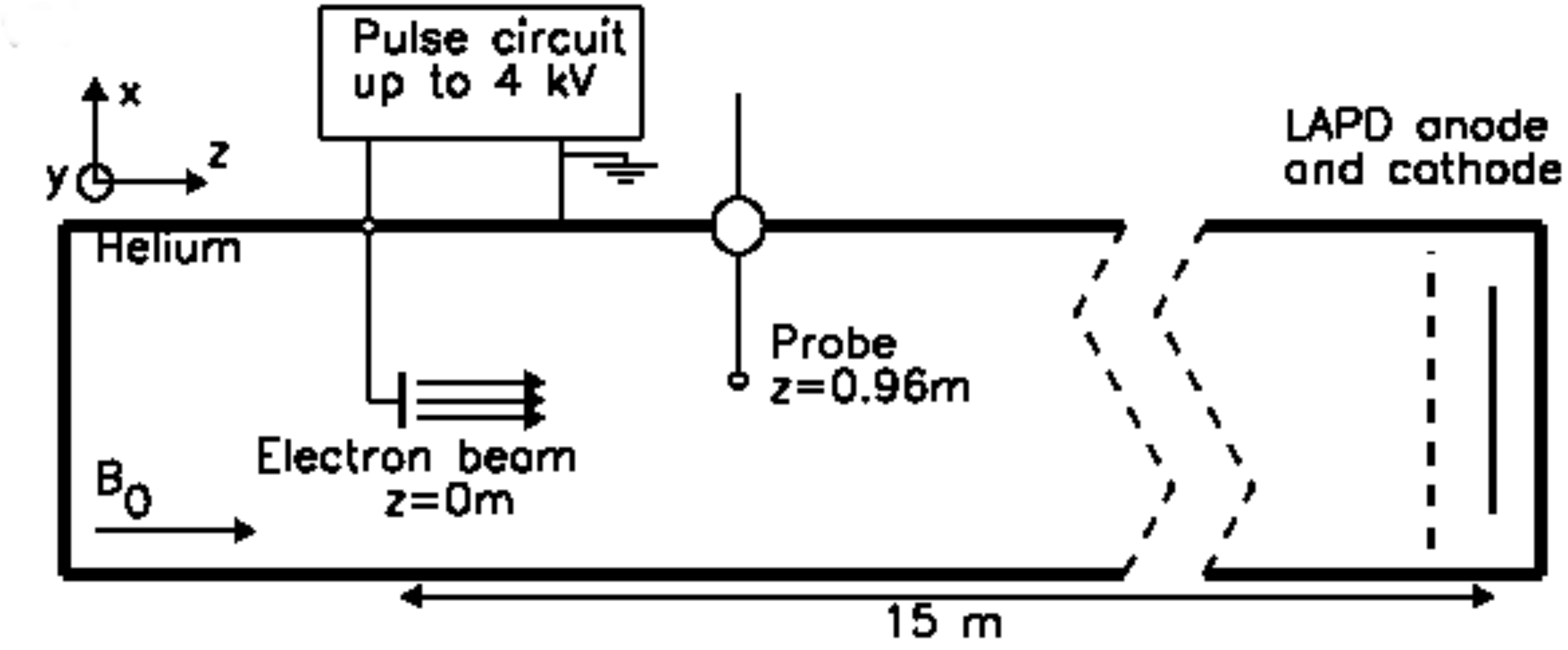

Strumik et al. (2015) GRL

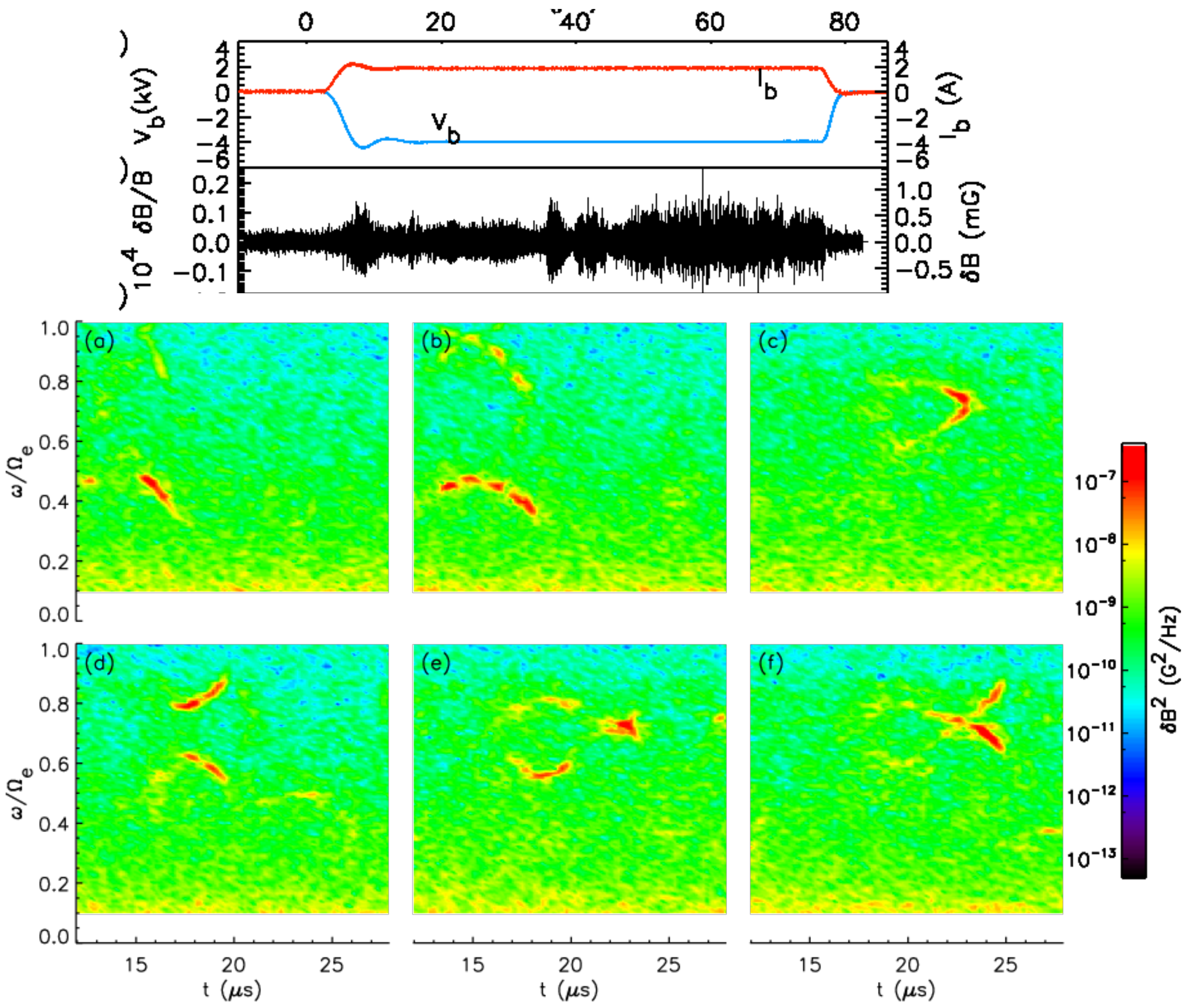
- With parallel drive, see development of instability that is thought to mediate quasi-parallel collisionless shocks: right-hand resonant instability (RHI). Relevant to Earth's bow shock

P. Heuer et al., ApJL 891, L11 (2020)

# Production of whistler-chorus-like emission by energetic electrons

- J. Bortnik (UCLA): interested in studying interactions between energetic electrons and whistler waves; relevance to Earth's radiation belts



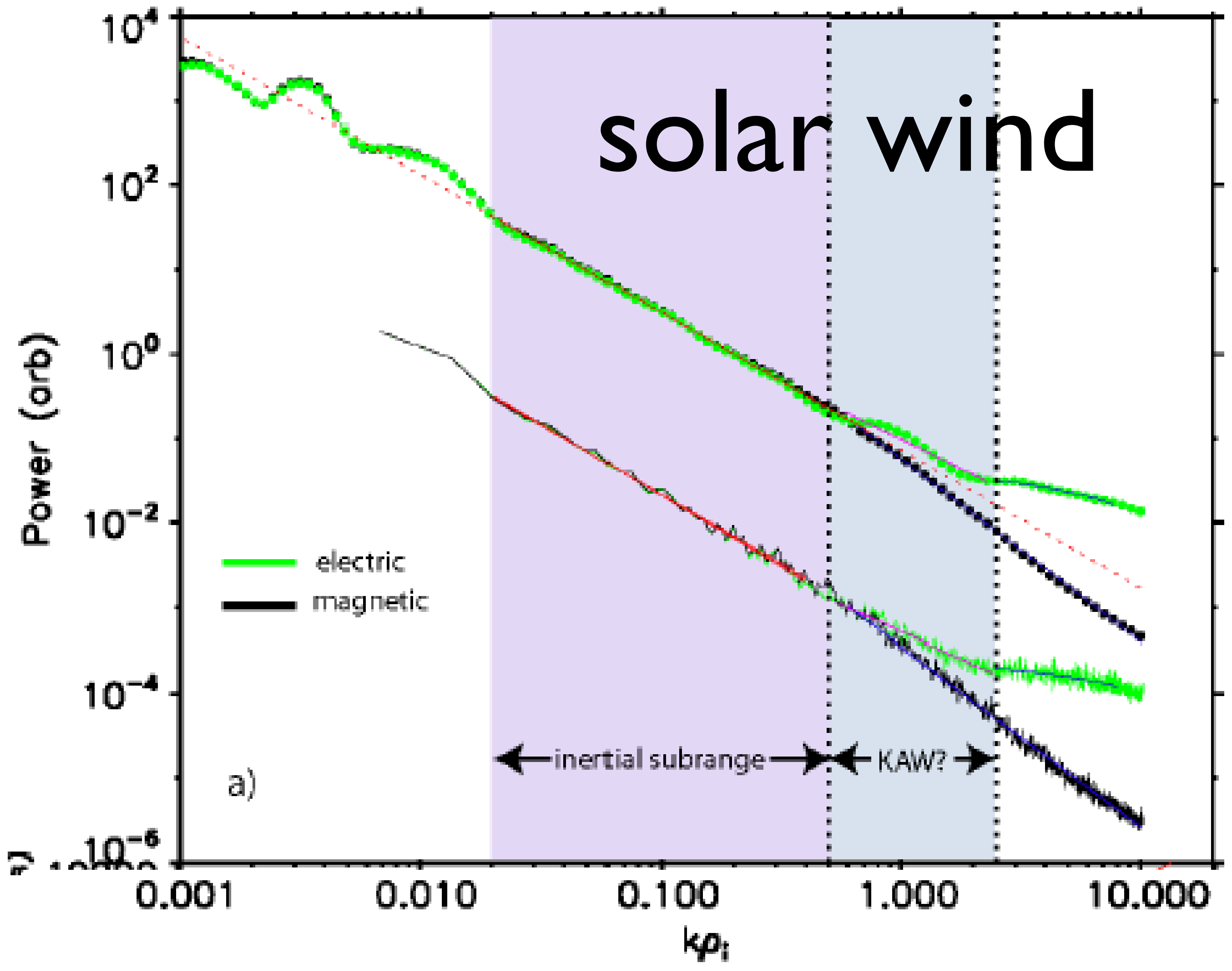




- Inject ~4 keV electron beam into LAPD; observe frequency chirped wave emission

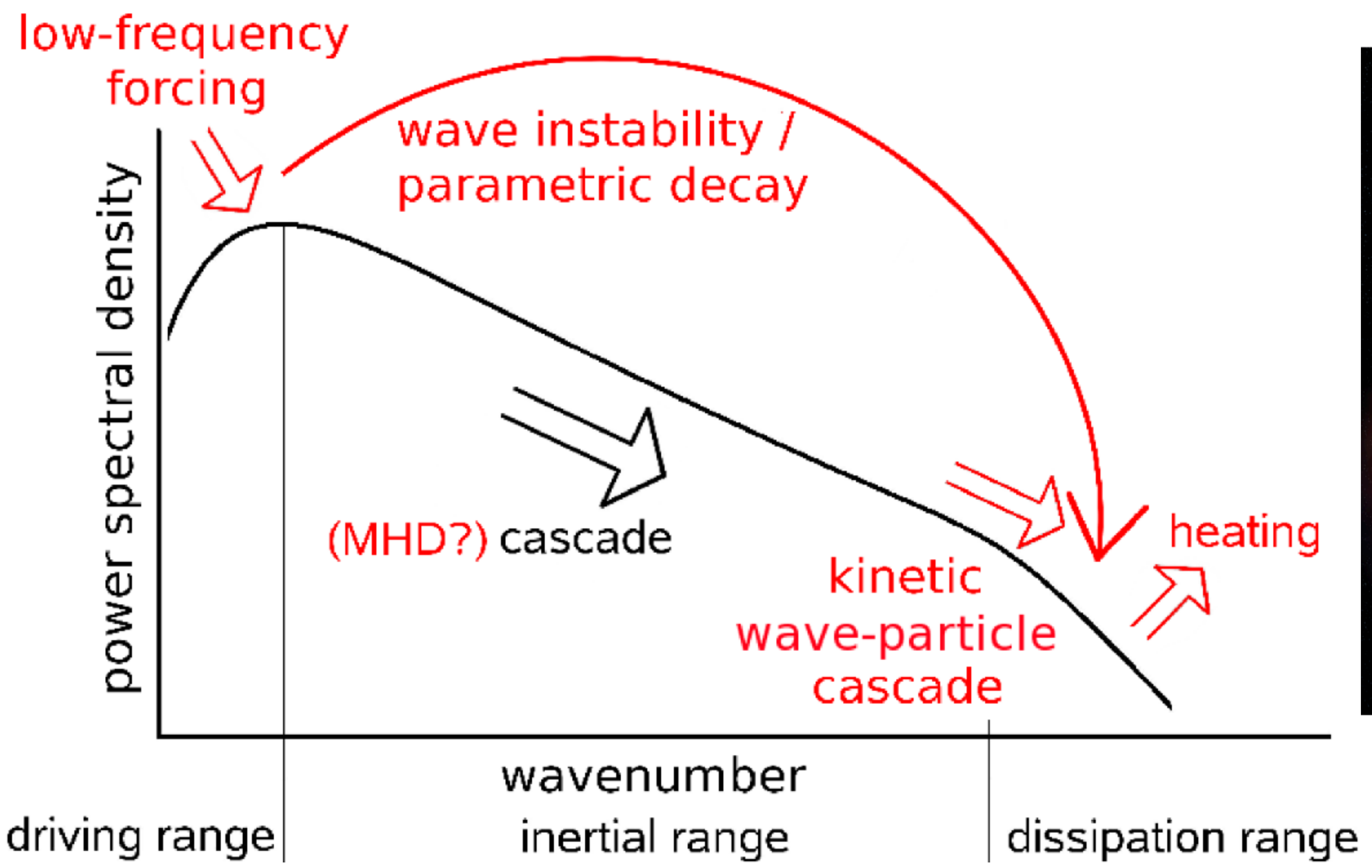
Van Compernolle, et al., Phys. Rev. Lett. 114, 245002 (2015)

An, et al. Geophys. Res. Lett., 43, 2413–2421 (2016)

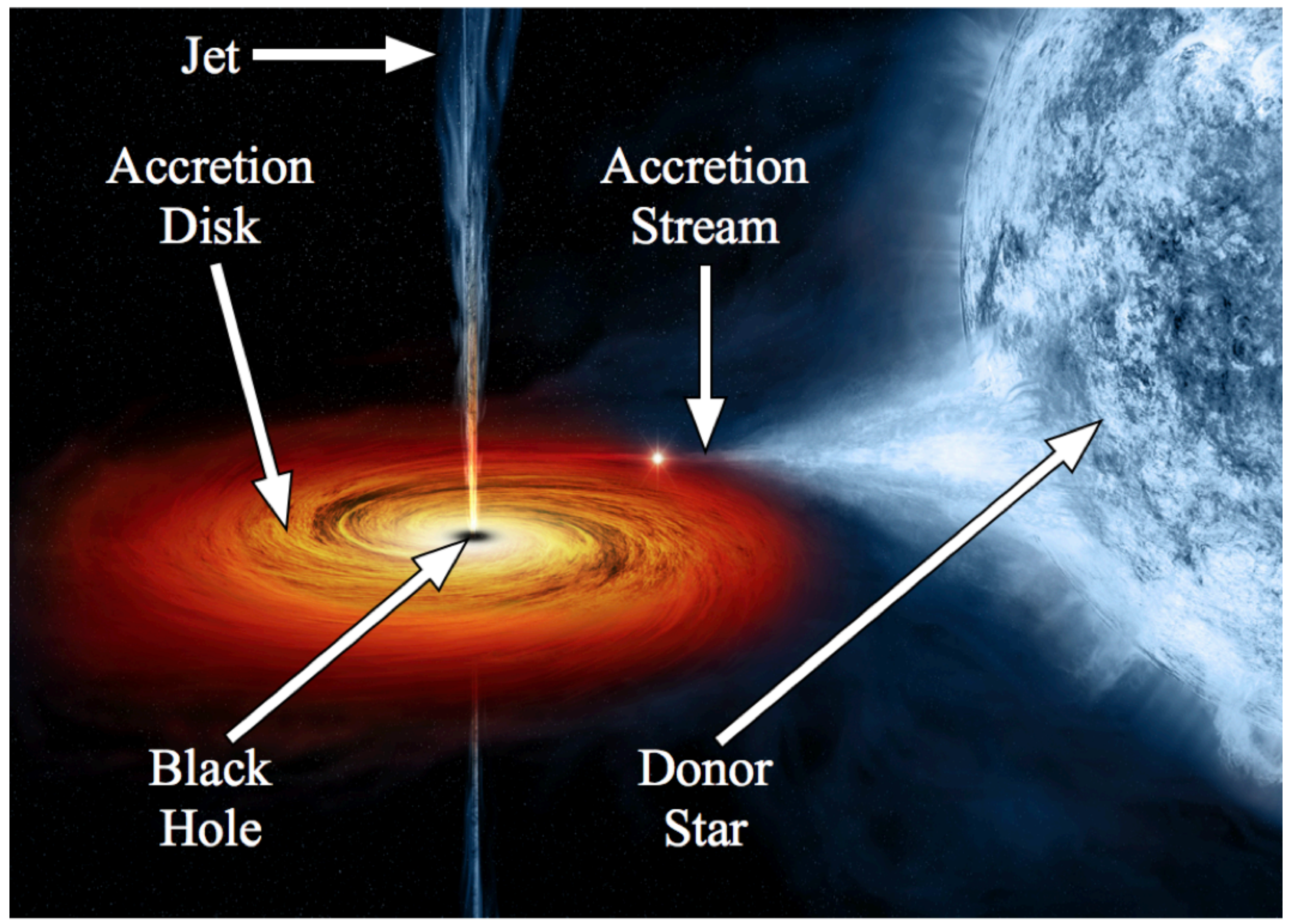
# Importance of nonlinear processes associated with Alfvén waves




(Bale et al. 2005)



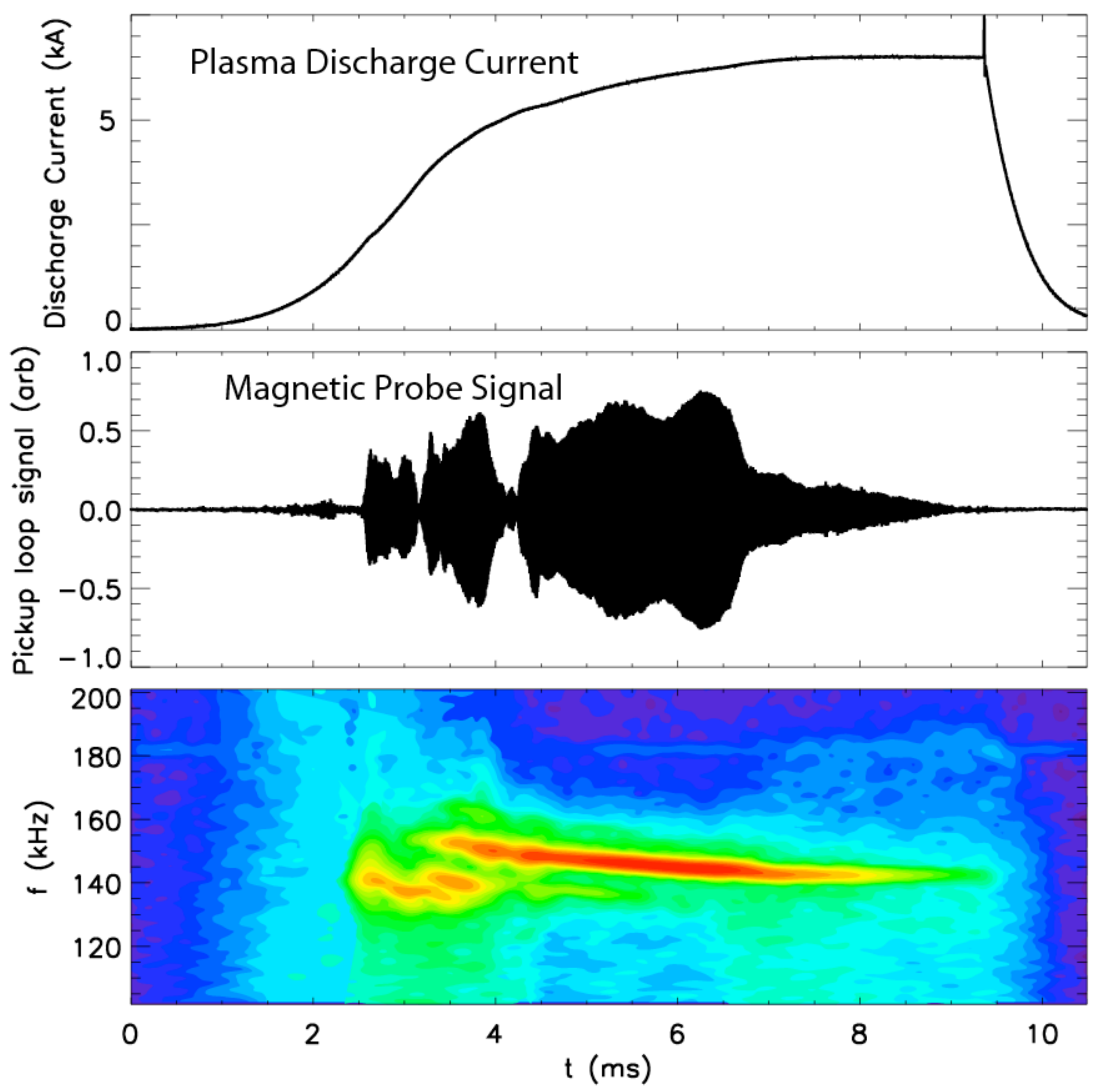

D.Verscharen

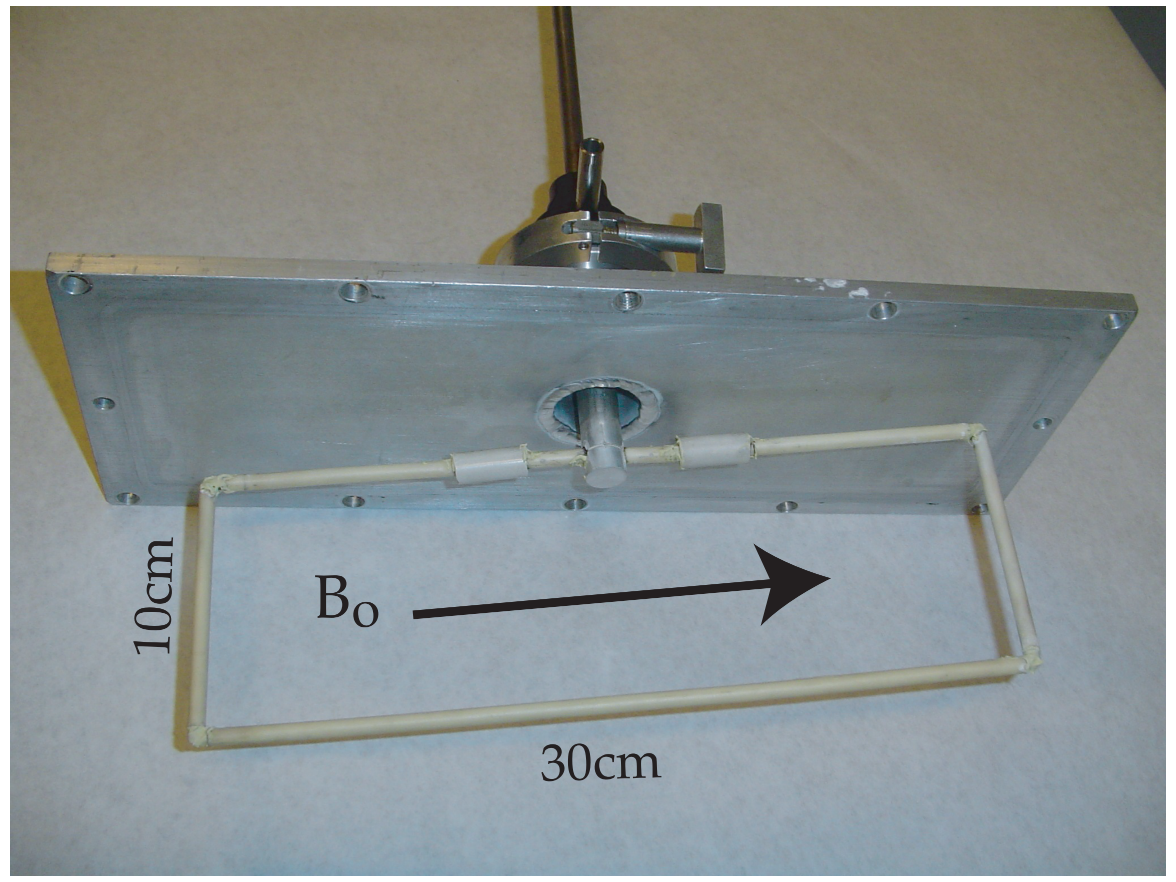


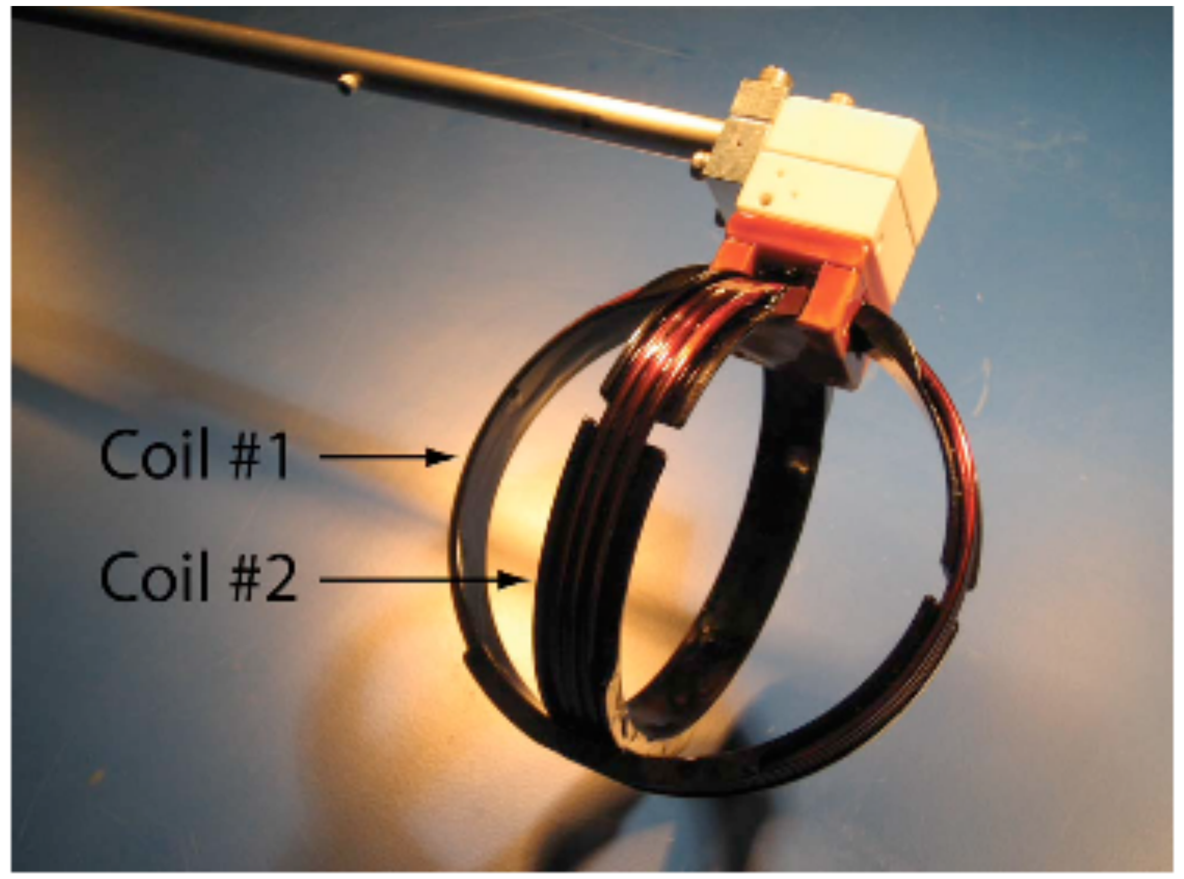

accretion disk

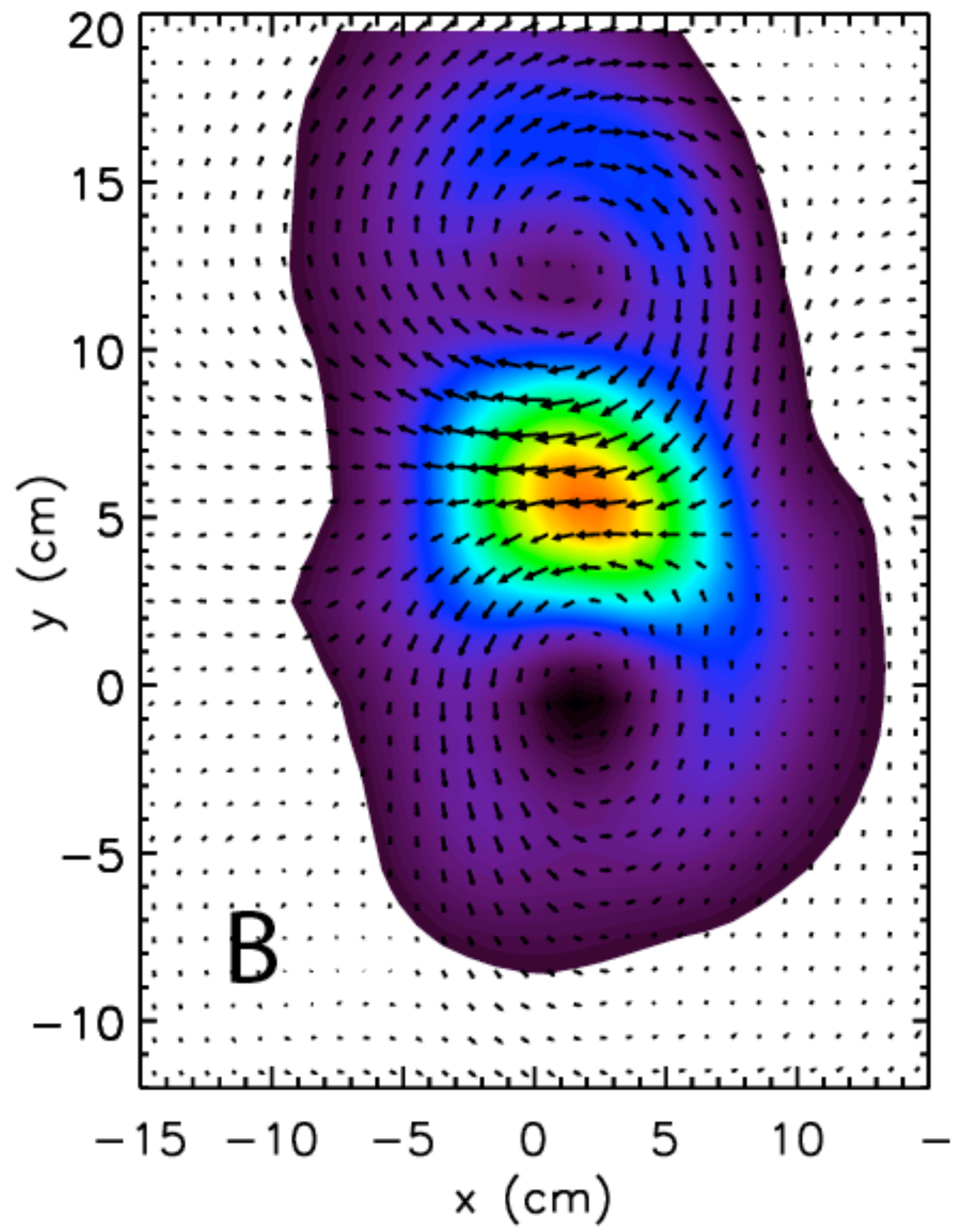
- Alfvénic turbulence: inertial range mediated by Alfvén three-wave interactions; dissipation scale (e.g. heating in solar wind and accretion disks) potentially explained by damping of Alfvén waves
- Decay instabilities: parametric decay (AW → AW + Sound Wave), e.g. might help generate counter-propagating spectrum of AWs in solar corona/solar wind or possibly bypass cascade

# Making large amplitude Alfvén waves in the lab



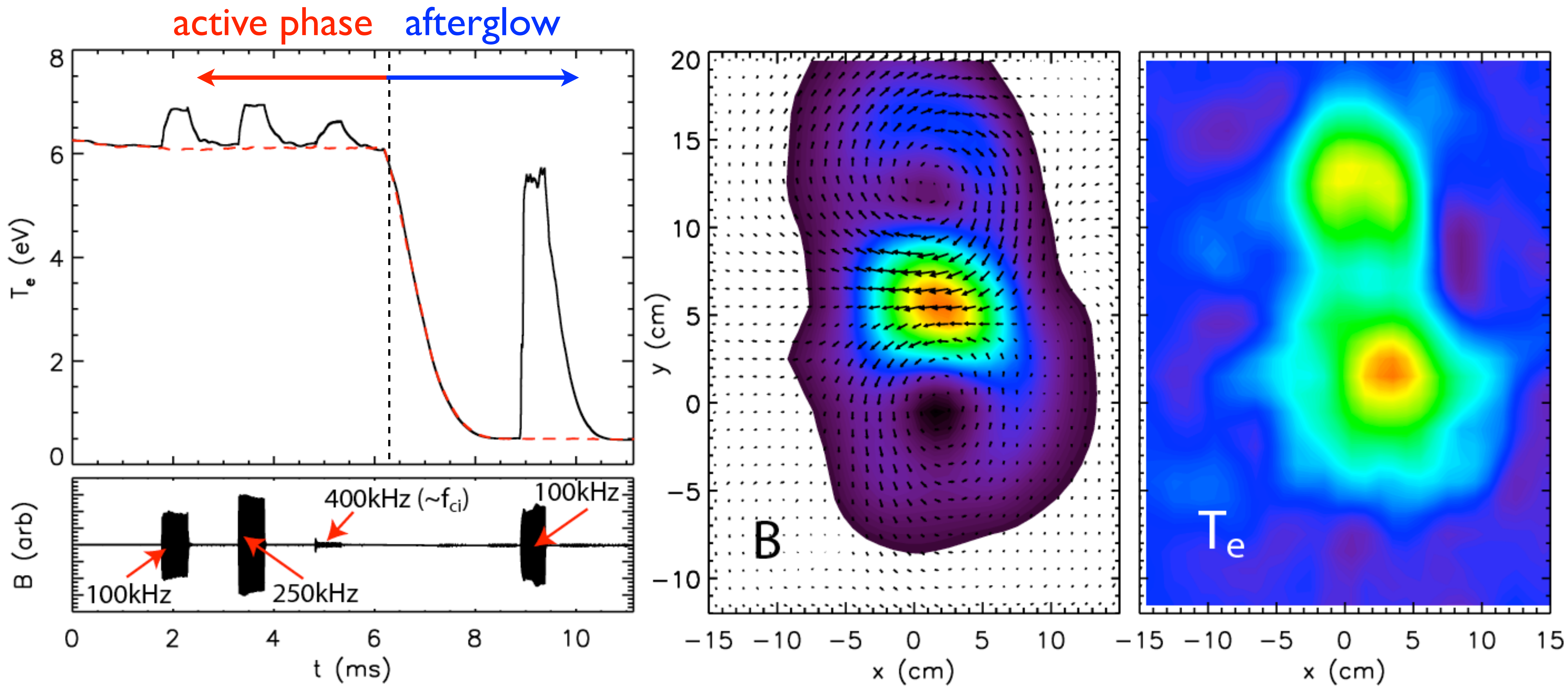



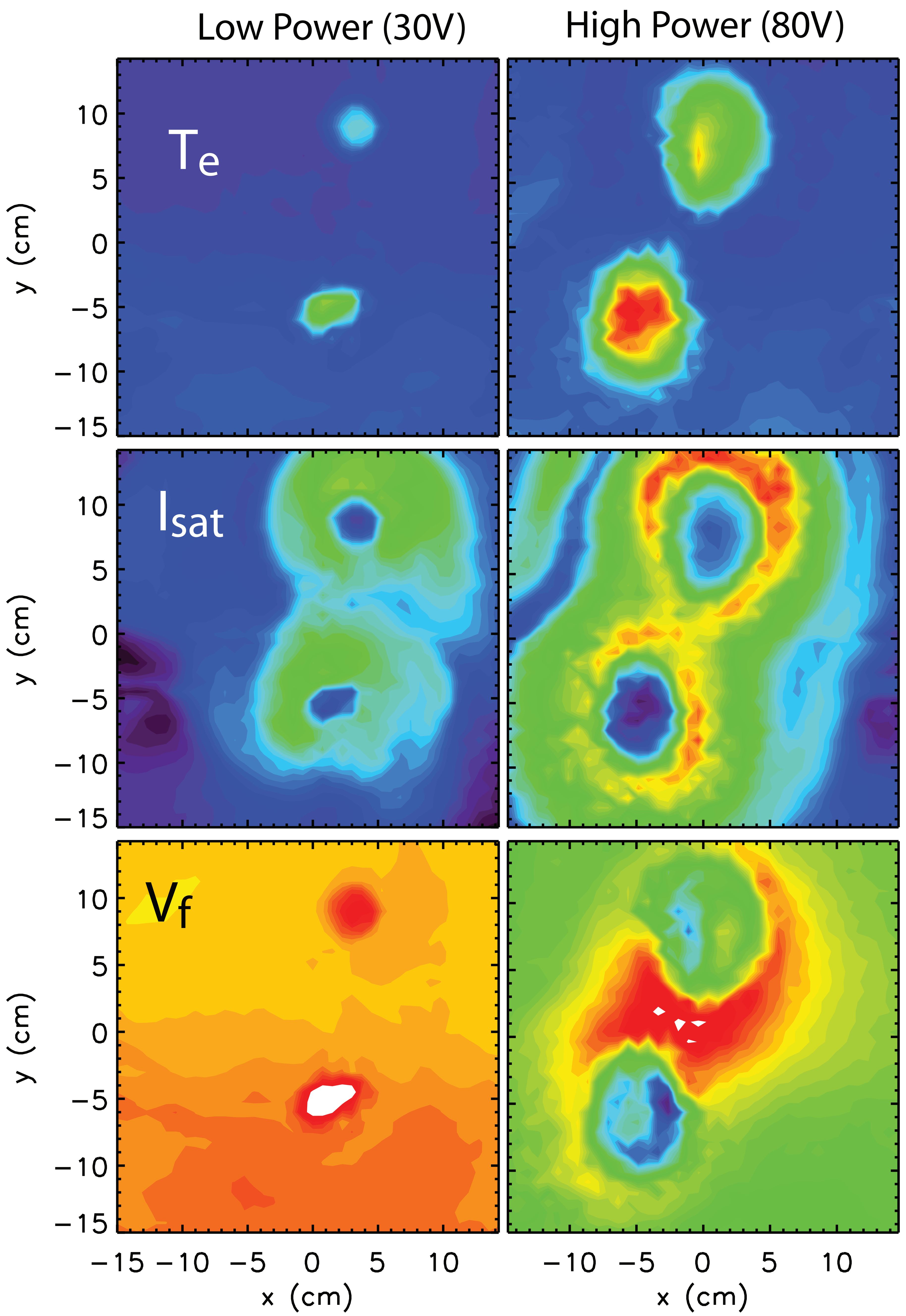




- Resonant cavity (MASER, narrowband), loop antenna (wideband)
- Both can generate AWs with $\delta B/B \sim 1\%$ (~10G or 1mT); large amplitude from several points of view:
  - From GS theory: stronger nonlinearity for anisotropic waves; here $k_{||}/k_{\perp} \sim \delta B/B$
  - Wave beta is of order unity $\beta_w = \dfrac{2\mu_o p}{\langle \delta B^2 \rangle} \approx 1$
  - Wave Poynting flux ~ 200 kW/m², same as discharge heating power density

# Strong electron heating by large amplitude Alfvén waves in LAPD



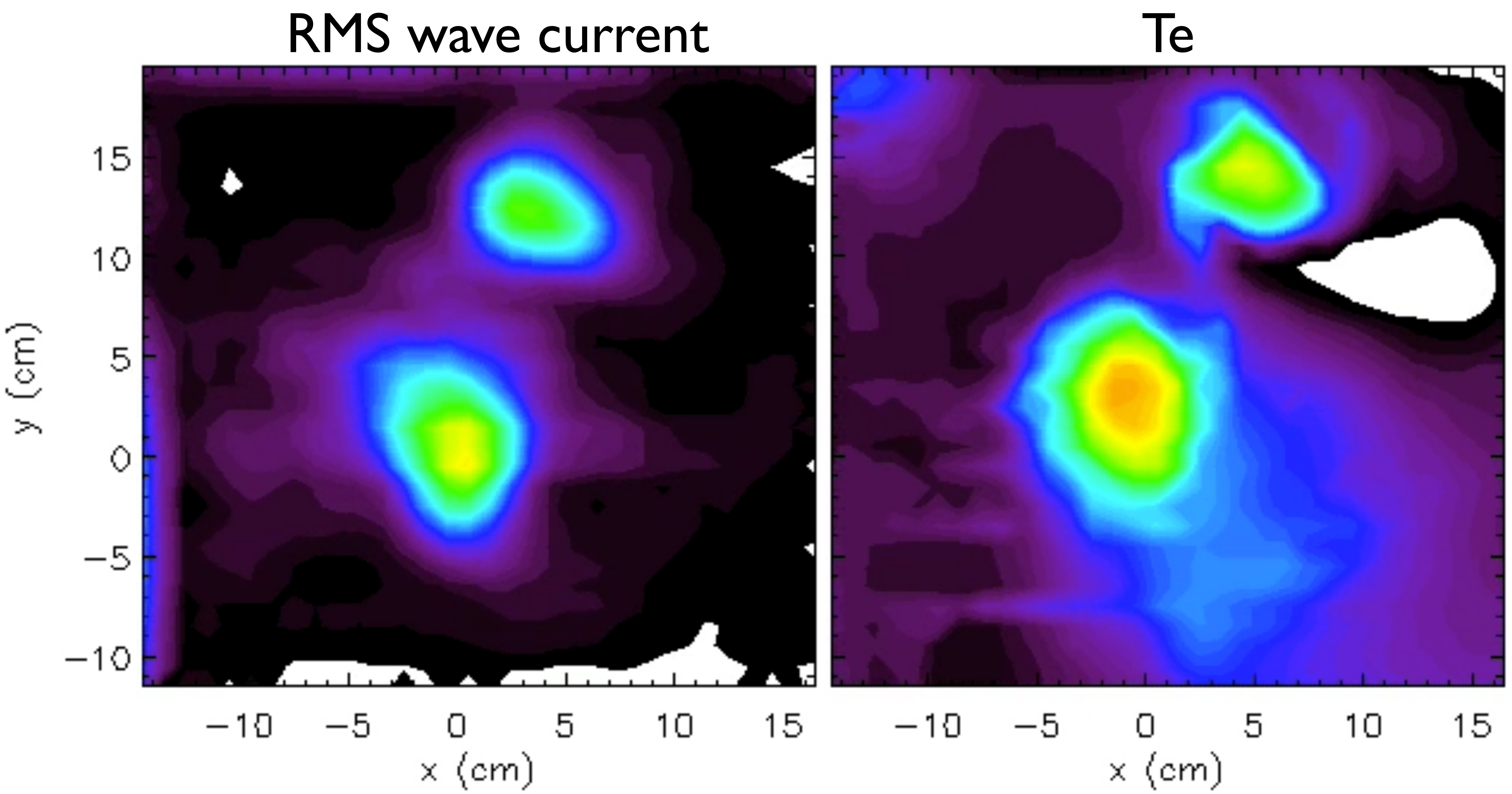

- Localized heating observed, on wave current channel (collisional and Landau damping: Note damping length is comparable to machine length!)
- Results in structuring of plasma (additionally see parallel outflows, density, potential modification, cross-field flows)




# Temperature, density and potential structuring by AW heating

- Strong heating on wave current channels
- Density depletion on current channel (density enhancement surrounding)
- Current channels tilt at high amplitude (due to potential, ExB flow? Consistent direction)
- Effect of structuring on wave propagation?

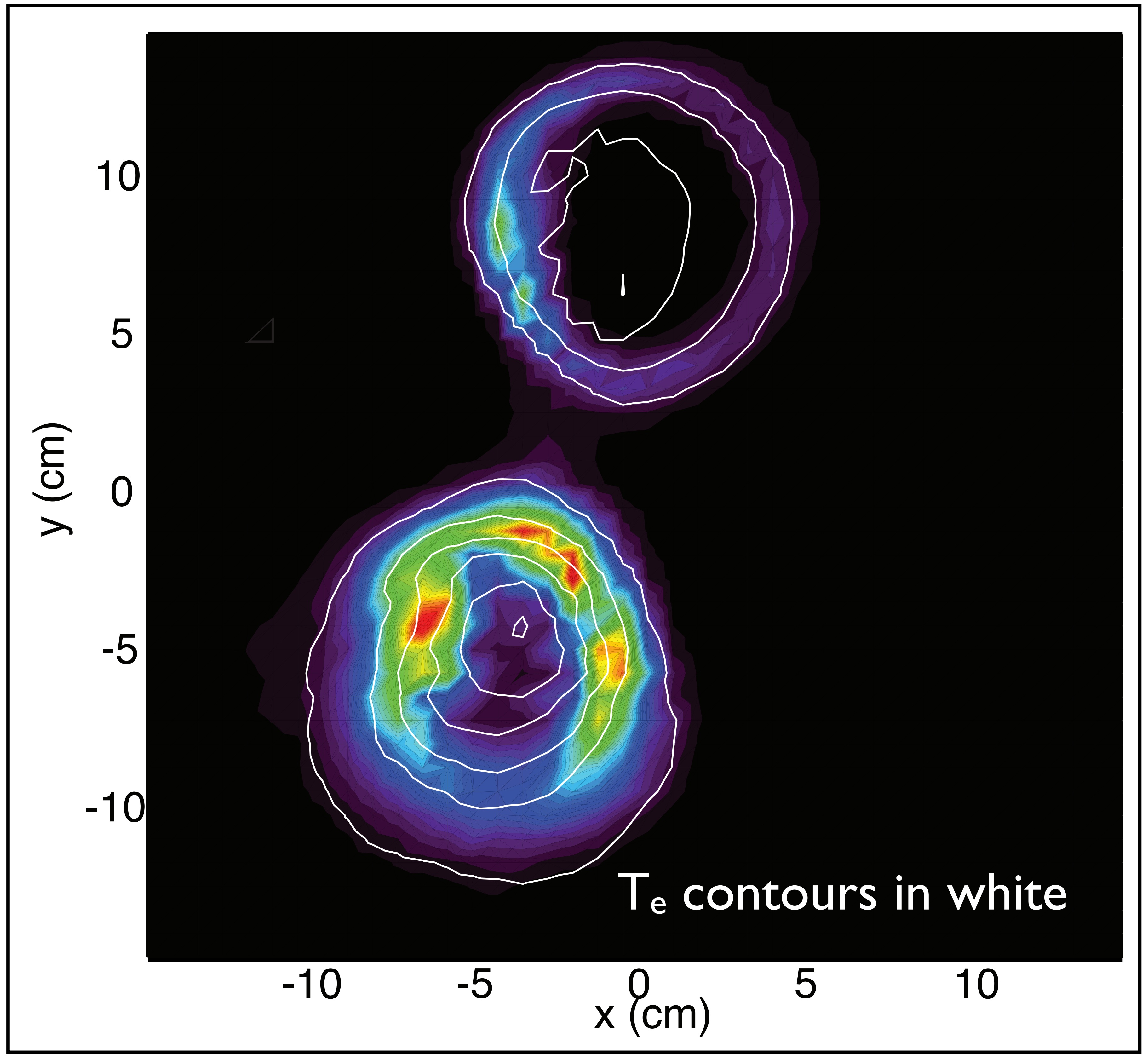
# Movie of heating during afterglow: dynamics of wave current channels and heated region



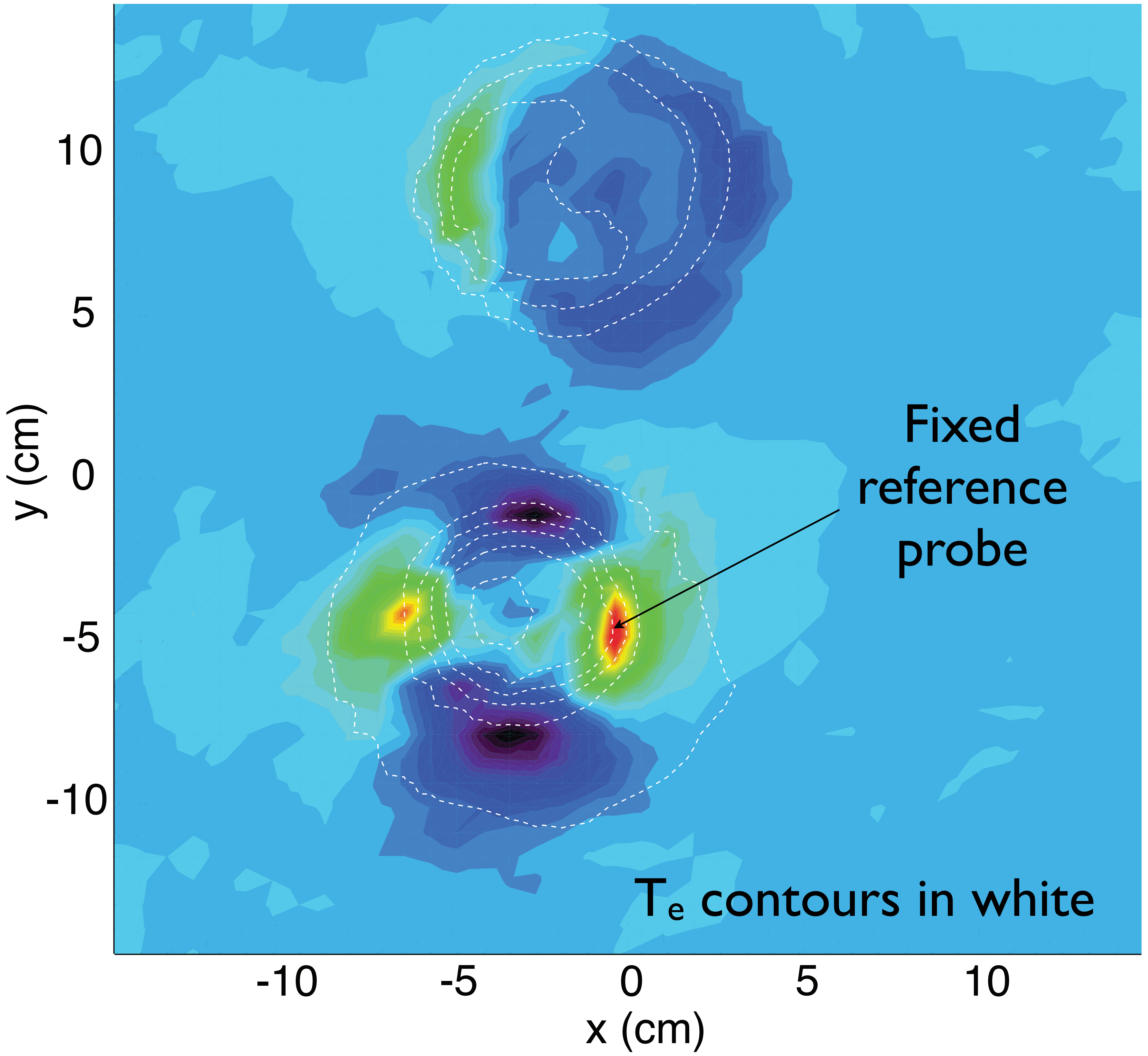

- Low frequency fluctuations observed, current channel wanders
- Drift-Alfvén waves driven by temperature gradients?

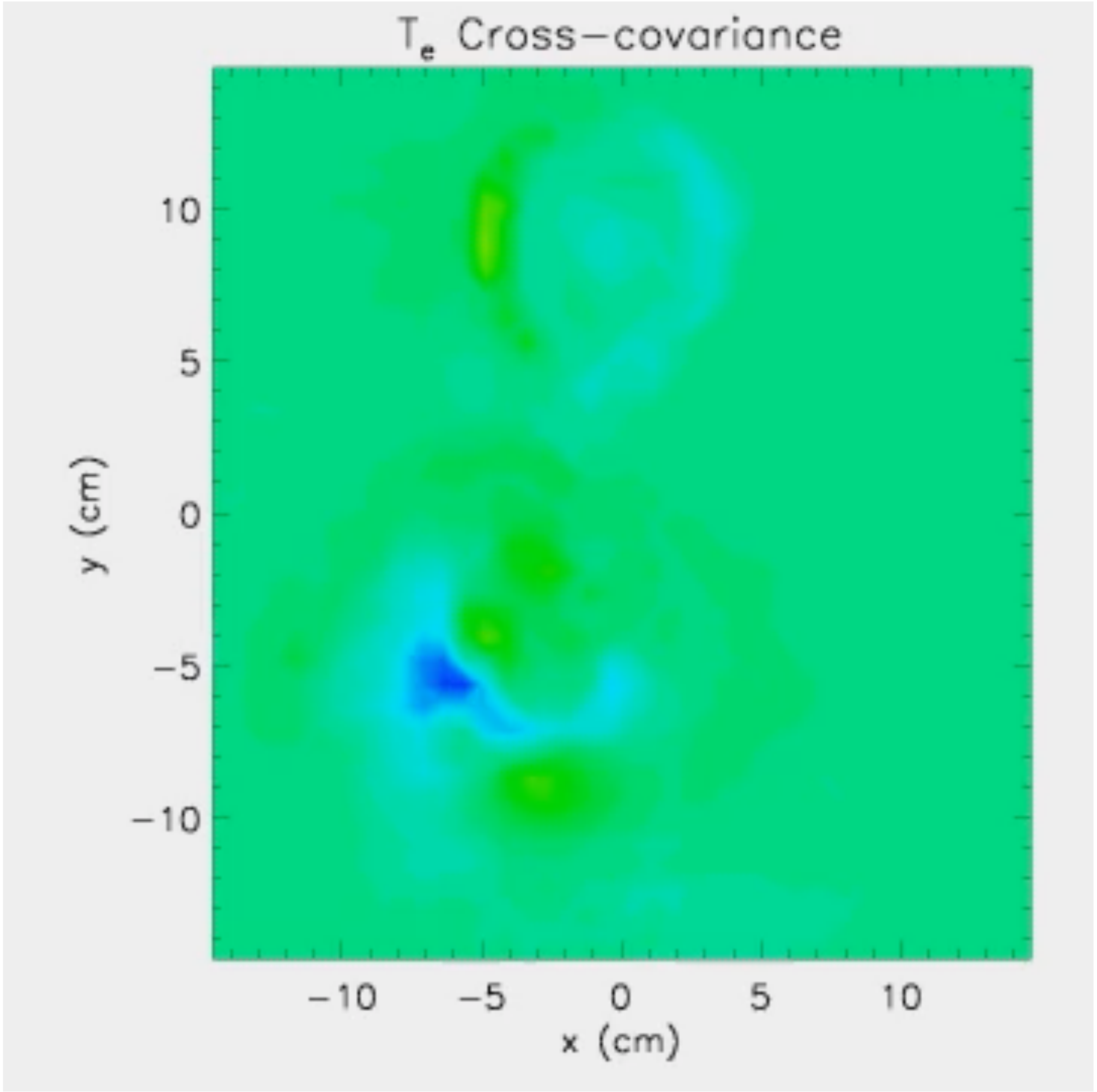
# Low frequency fluctuations observed on heating-produced temperature gradients: consistent with unstable drift-Alfvén waves

$T_e$ fluctuations



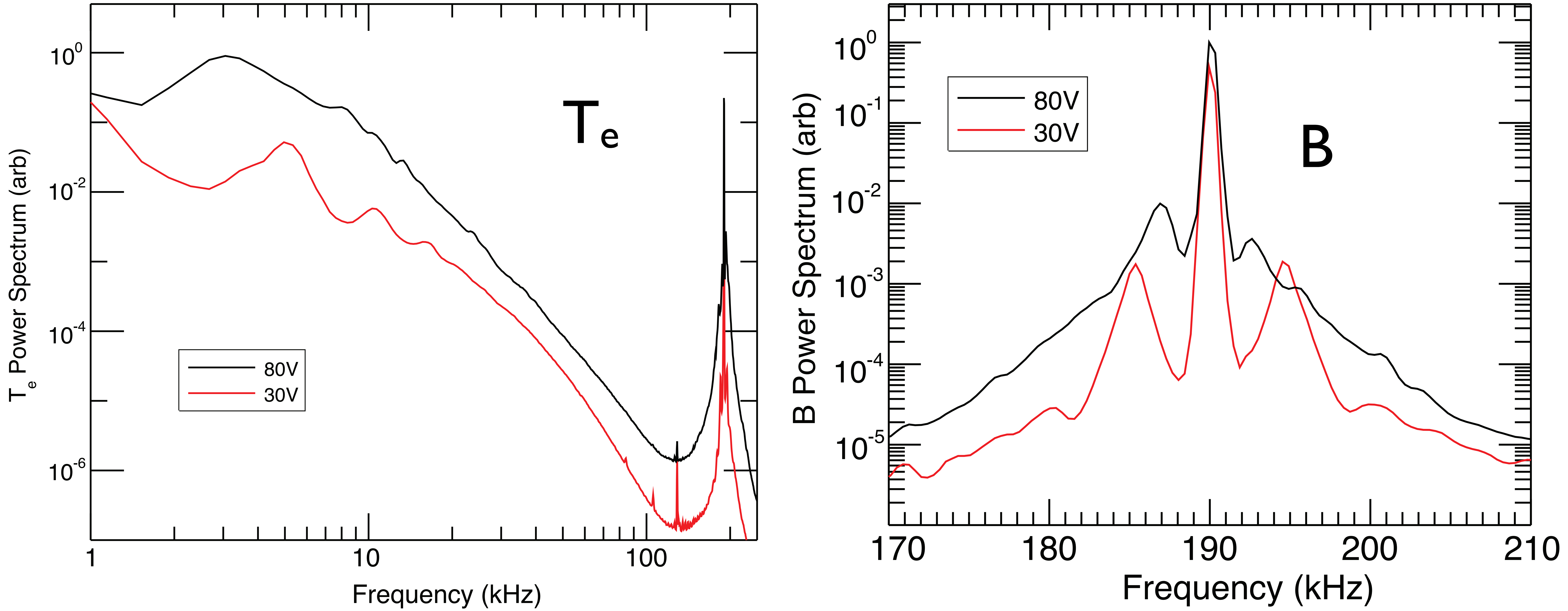

$T_e$ cross-covariance




- Fluctuations localized to edge of heated region, correlation measurements reveal m=2 dominant mode consistent with resistive drift-Alfvén waves

# Sideband generation and turbulent broadening of AW from interaction with drift-Alfvén fluctuation

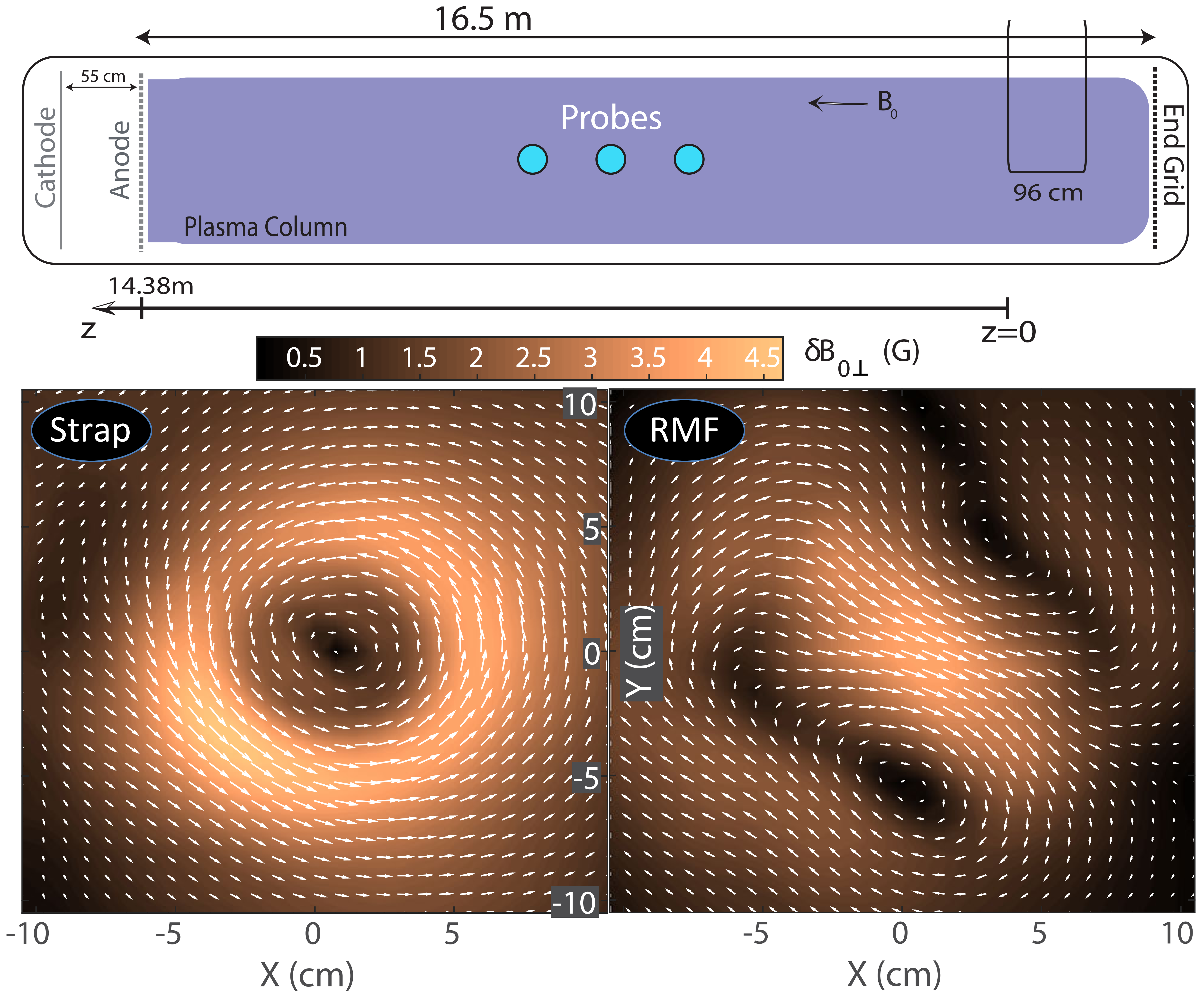



- Sidebands separated by dominant drift-Alfvén wave frequency
- Larger drift wave frequency at lower power: smaller heated channel

# Nonlinear studies of Alfvén waves in LAPD

- Series of experiments exploring three-wave interactions and decay instabilities. Motivations include studying Alfvénic turbulence in the lab
- Collision of two antenna-launched shear Alfvén waves:
  - Two co-propagating AWs produce a quasimode [Carter, et al., PRL, 96, 155001 (2006)]
  - Two co-propagating KAWs drive drift waves, lead to control/ suppression of unstable modes (in favor of driven stable mode) [Auerbach, et al., PRL, 105, 135005 (2010)]
  - Two counter-propagating AWs, one long wavelength ($k_{\parallel} \approx 0$), produce daughter AW (building block of MHD turbulent cascade) [Howes, et al., PRL, 109, 255001 (2012)]
  - Two counter-propagating AWs nonlinearly excite an ion acoustic wave [Dorfman & Carter, PRL, 110, 195001 (2013)]
- Parametric instability of single large-amplitude shear wave [Dorfman & Carter, PRL, 116, 195002 (2016)]

# Observation of a parametric instability of kinetic Alfvén waves in LAPD

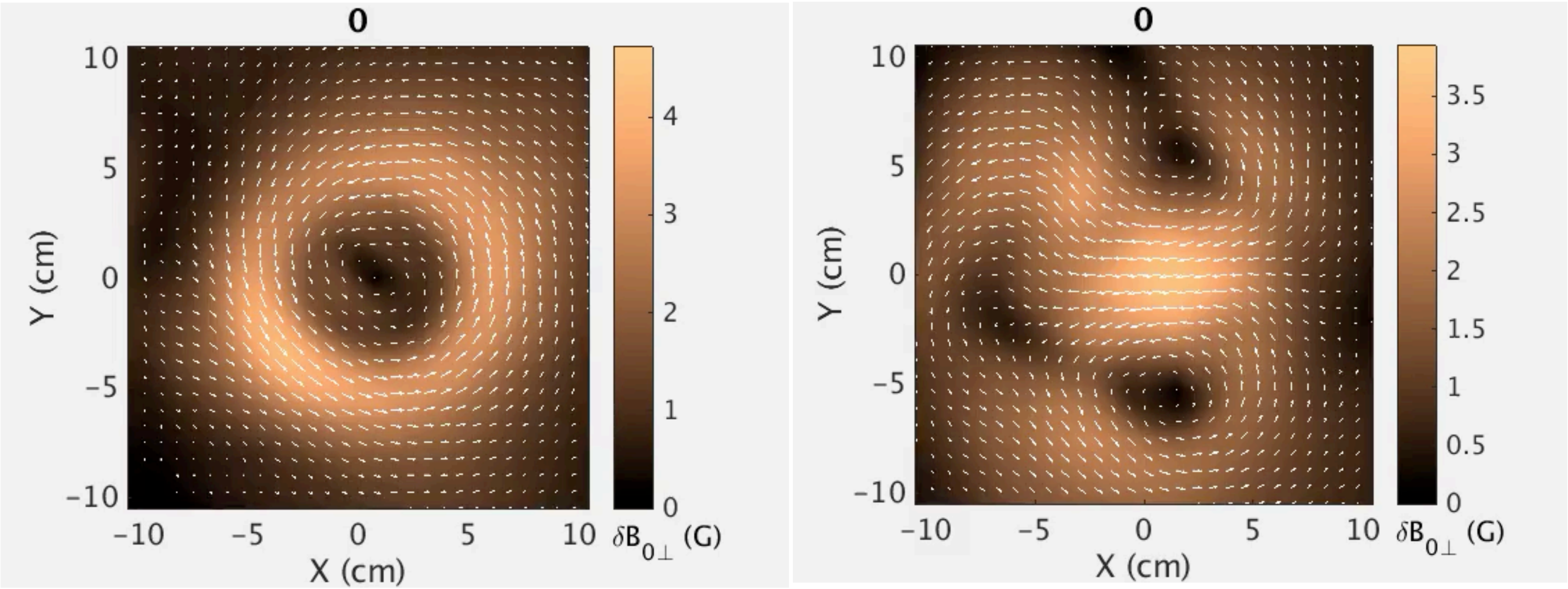



Pump wave spatial patterns (two different kinds of antennas)

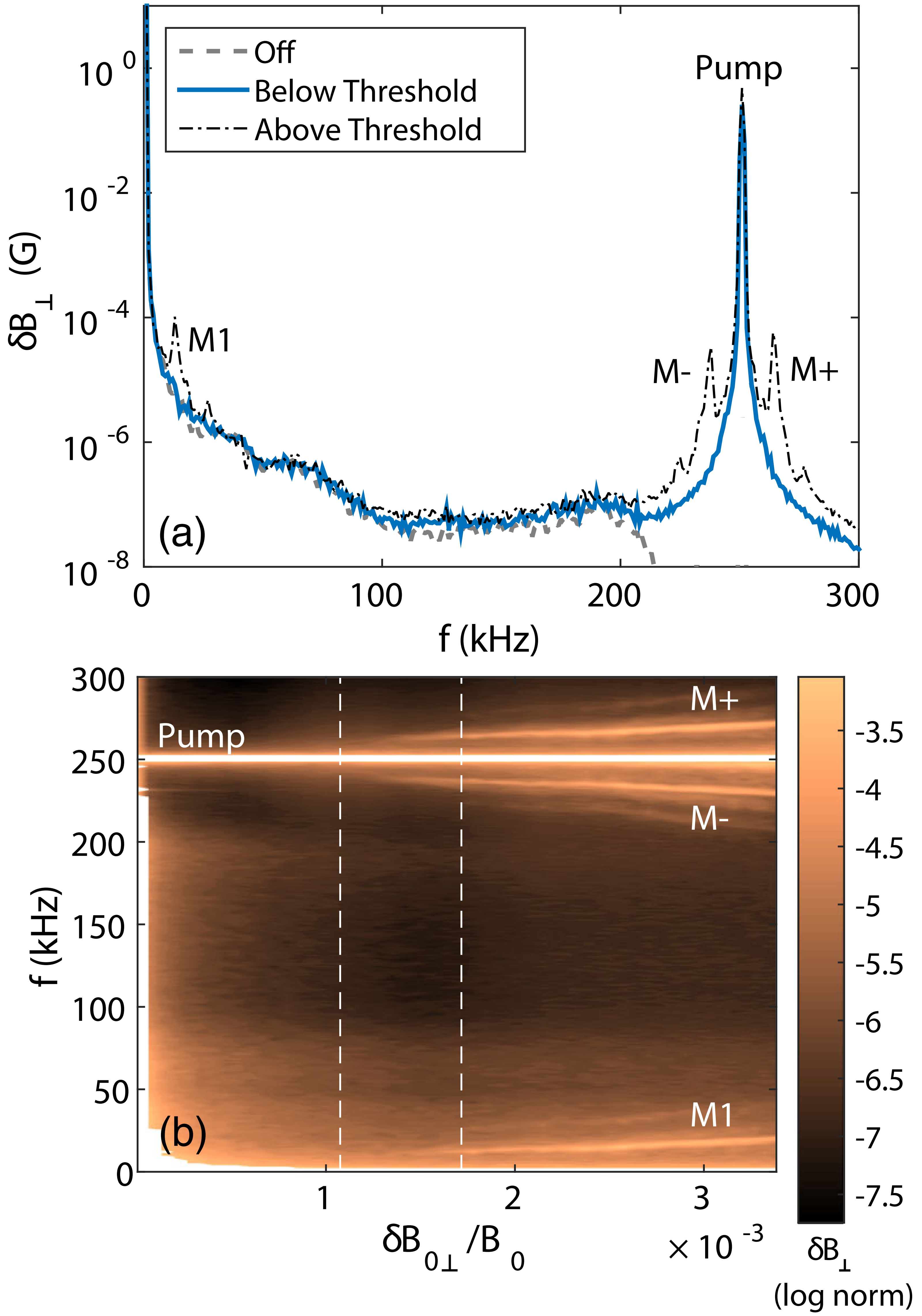
- Single, large amplitude KAW launched. Above an amplitude threshold and frequency, observe production of daughter modes.

[Dorfman & Carter, PRL, 116, 195002 (2016)]

# Pump waves: linearly and circularly polarized

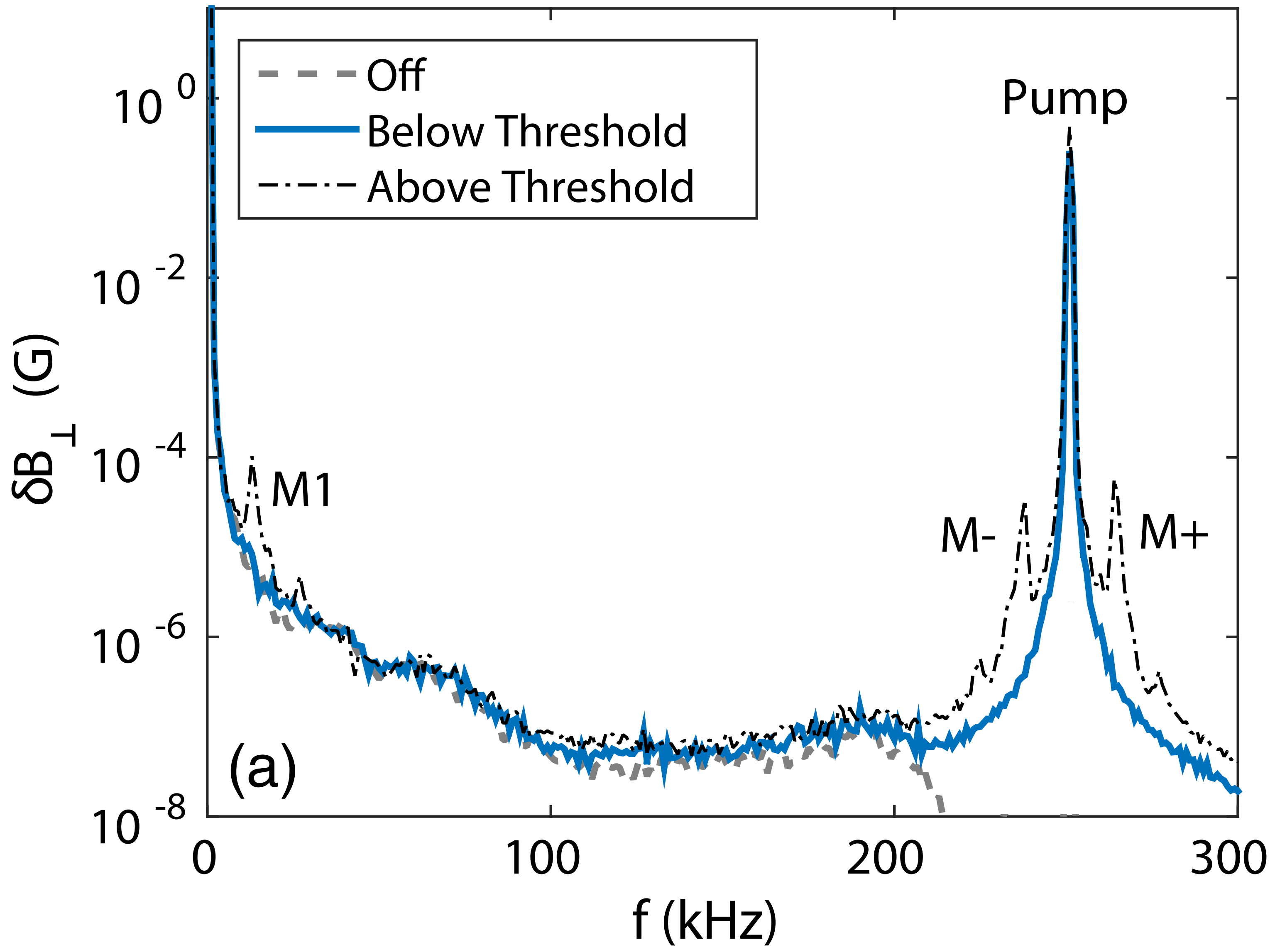


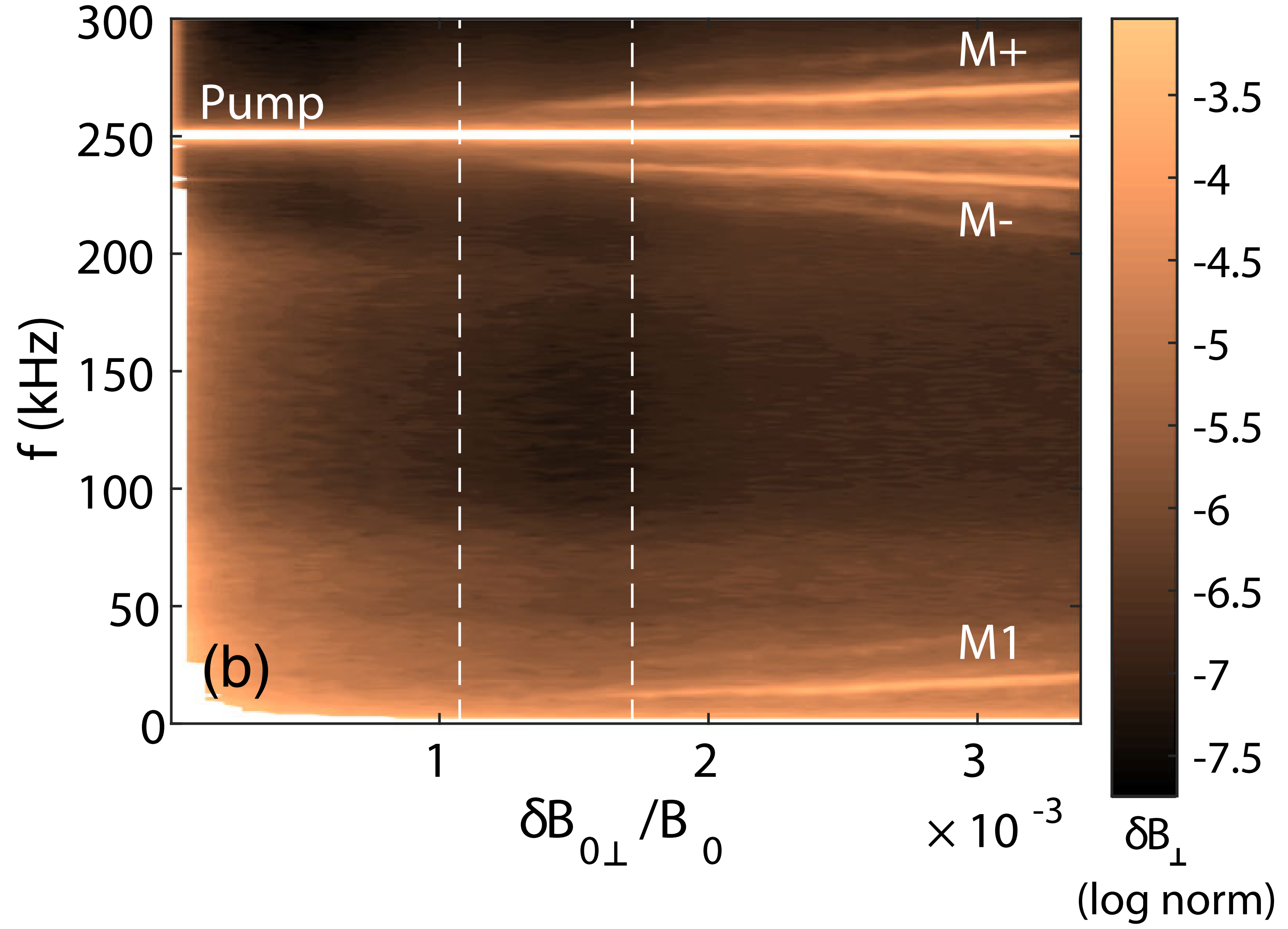
# Above a threshold in pump amplitude, see production of sidebands and low frequency mode

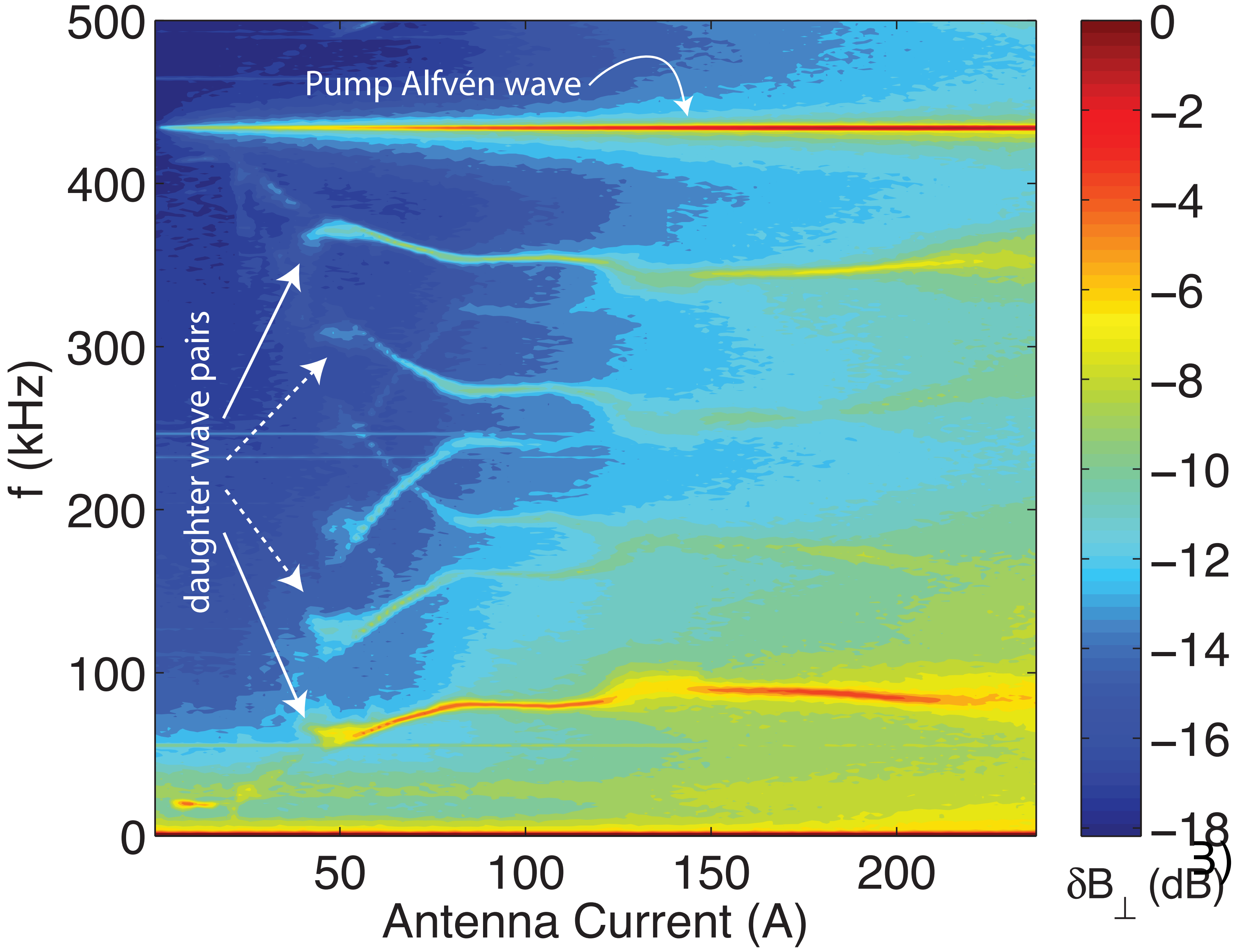



- Threshold in amplitude and in pump frequency (only observed for $f \gtrsim 0.5\ f_{ci}$)
- All three daughter waves co-propagating with pump. Need dispersive AWs
- Modes satisfy three-wave matching rules

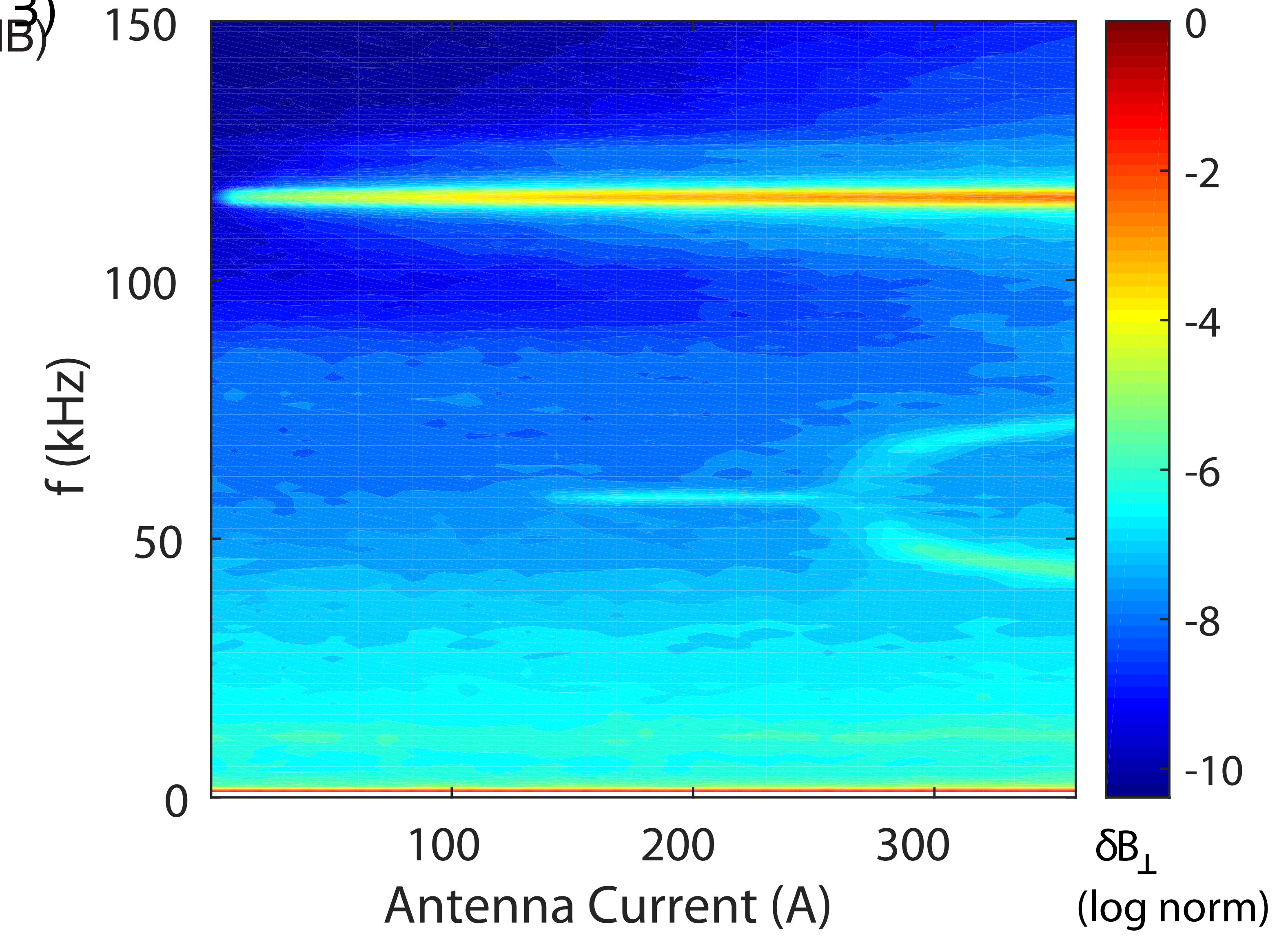
# Above a threshold in pump amplitude, see production of sidebands and low frequency mode



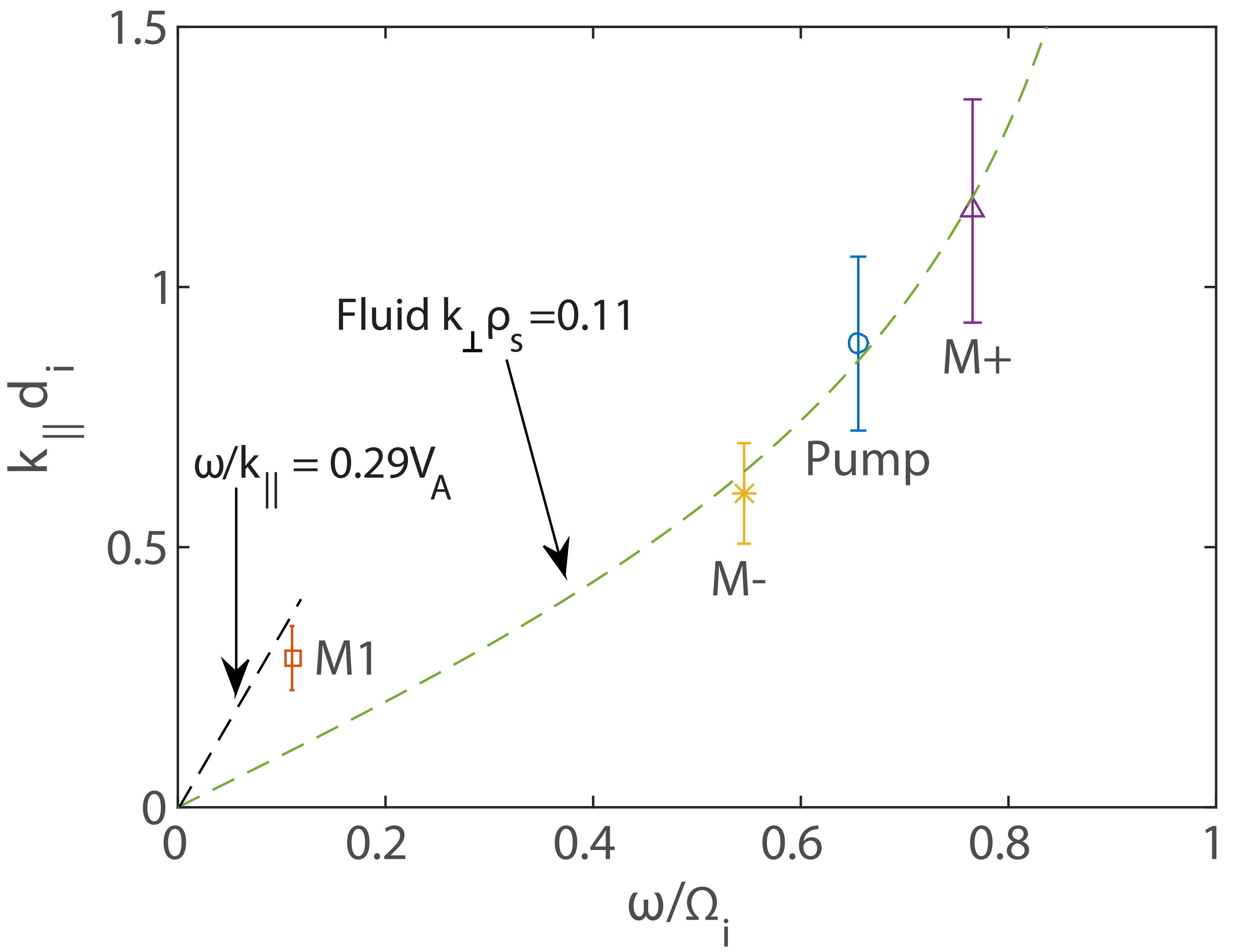



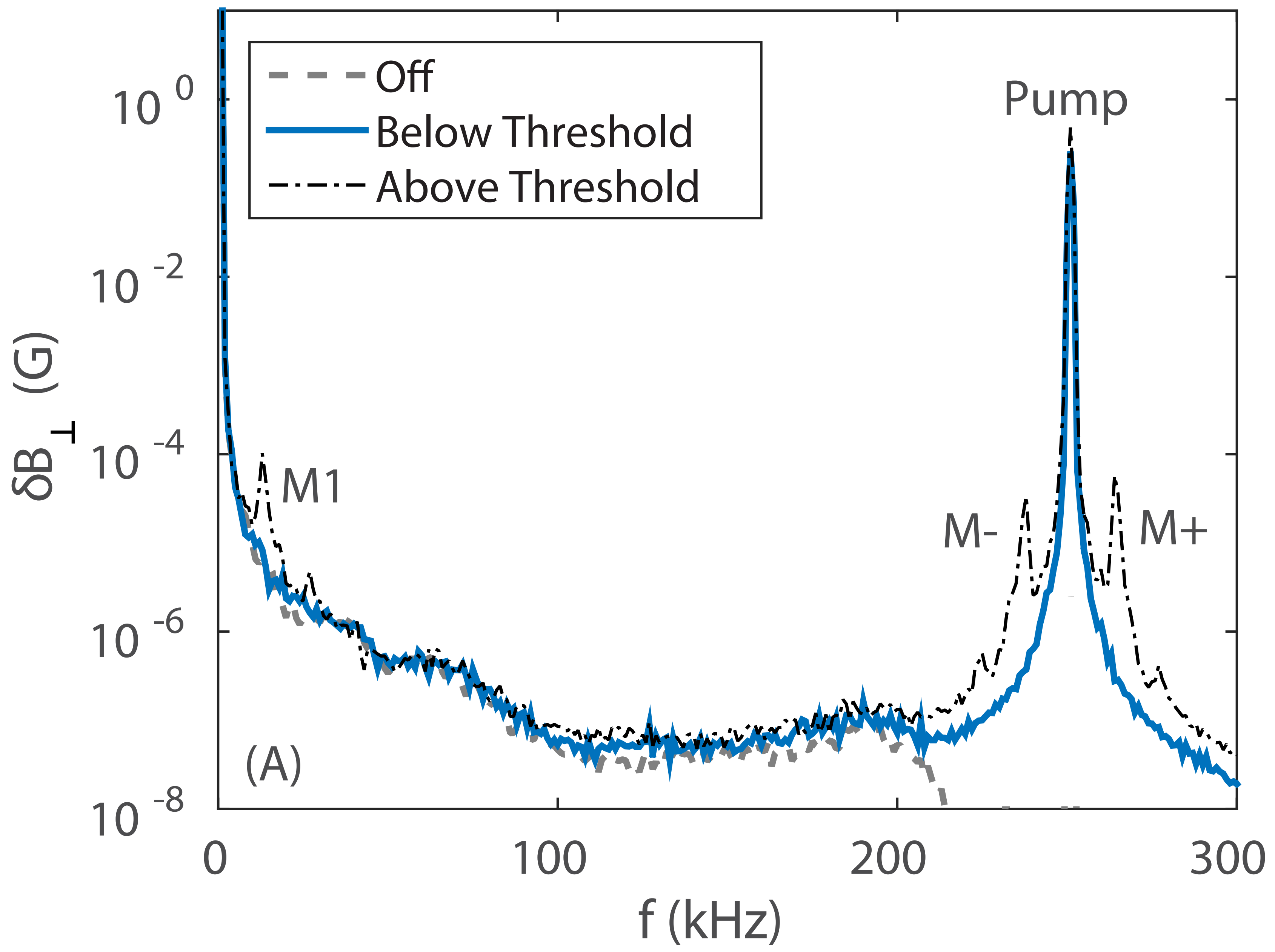




Variety of behaviors observed as plasma parameters are changed



# Sidebands are KAWs, low frequency mode is quasimode




- Sideband waves are consistent with KAW dispersion relation
- Low frequency mode is a non-resonant mode/quasimode: phase speed inconsistent with sound wave or KAW
- **Participant modes consistent with modulational decay instability (but why don't we see parametric decay?)**

[Dorfman & Carter, PRL, 116, 195002 (2016)]

# ICRF Campaign on LAPD: using fast waves/compressional Alfvén waves to heat, energize ions, drive current

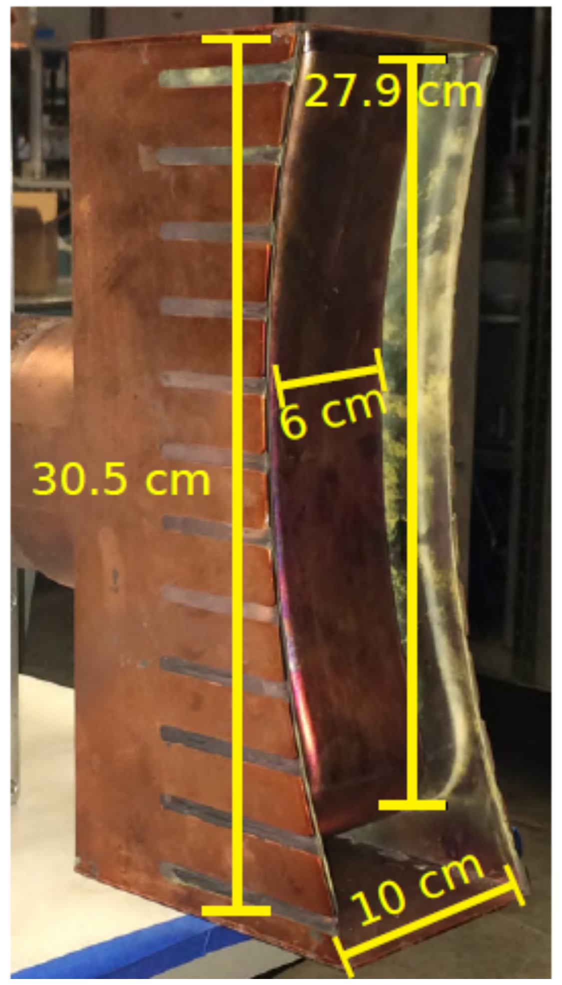
- Ion Cyclotron Range of Frequencies (ICRF) waves used to heat ions and electrons and drive current in fusion experiments
- Campaign led by C. Lau (ORNL) with participation from scientists at ORNL, MIT, PPPL, General Atomics, TAE Technologies, IPP, U. Ghent…
  - Coupling, physics of fast waves, helicon waves, novel heating schemes relevant to fusion experiments
  - Parasitic processes and their mitigation: **RF sheaths (& sputtering/PMI), coupling to slow mode,** parametric instabilities.

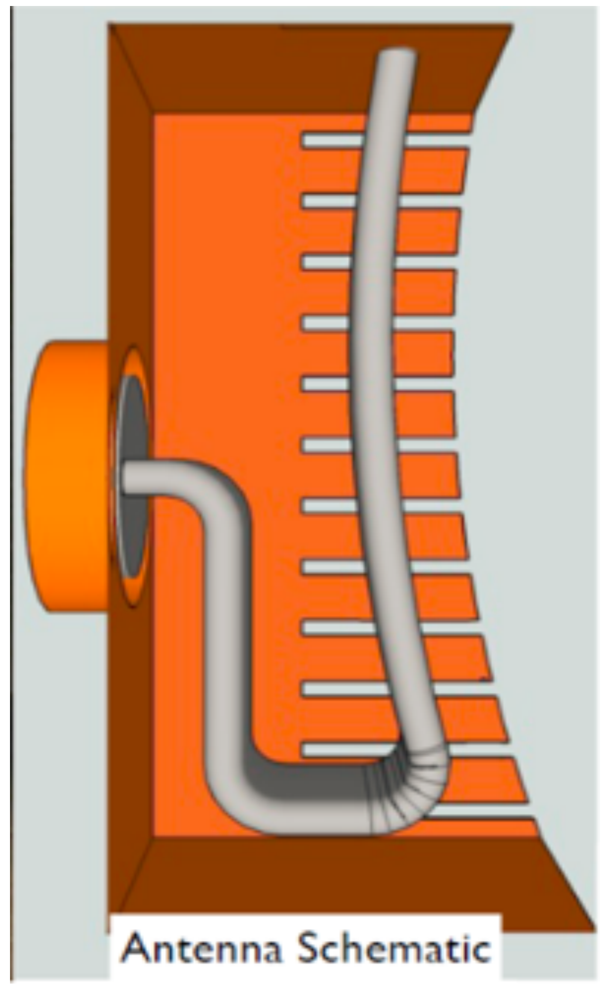
# RF Sheaths lead to impurity generation in fusion experiments

- Some fusion experiments, in particular those with High-Z PFCs (e.g. Tungsten on ASDEX-U), see impurity generation/influx during ICRF heating
  - Culprit is RF rectification of antenna near fields on antenna structures (and possibly also far-field rectification) - strong DC E fields result that accelerate ions into antenna structure and cause sputtering
  - Mitigation of these effects: field-aligned antenna (minimize parallel E, Alcator C-Mod) and reduced image currents using three-strap balanced current scheme (ASDEX-U)

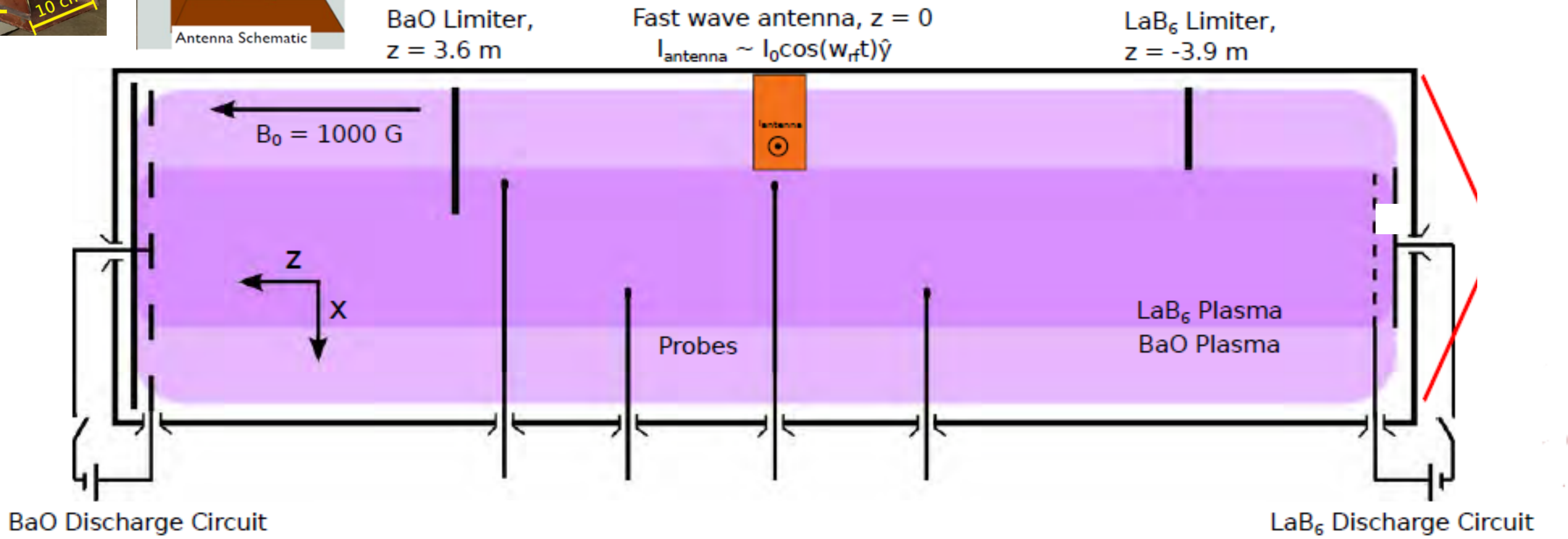
Neu R et al Plasma Phys. Control. Fusion 49 B59–70 (2007)
Wukitch et al Physics of Plasmas 20, 056117 (2013)
V Bobkov et al Plasma Phys. Control. Fusion 59 014022 (2017)

# LAPD single-strap ICRF System

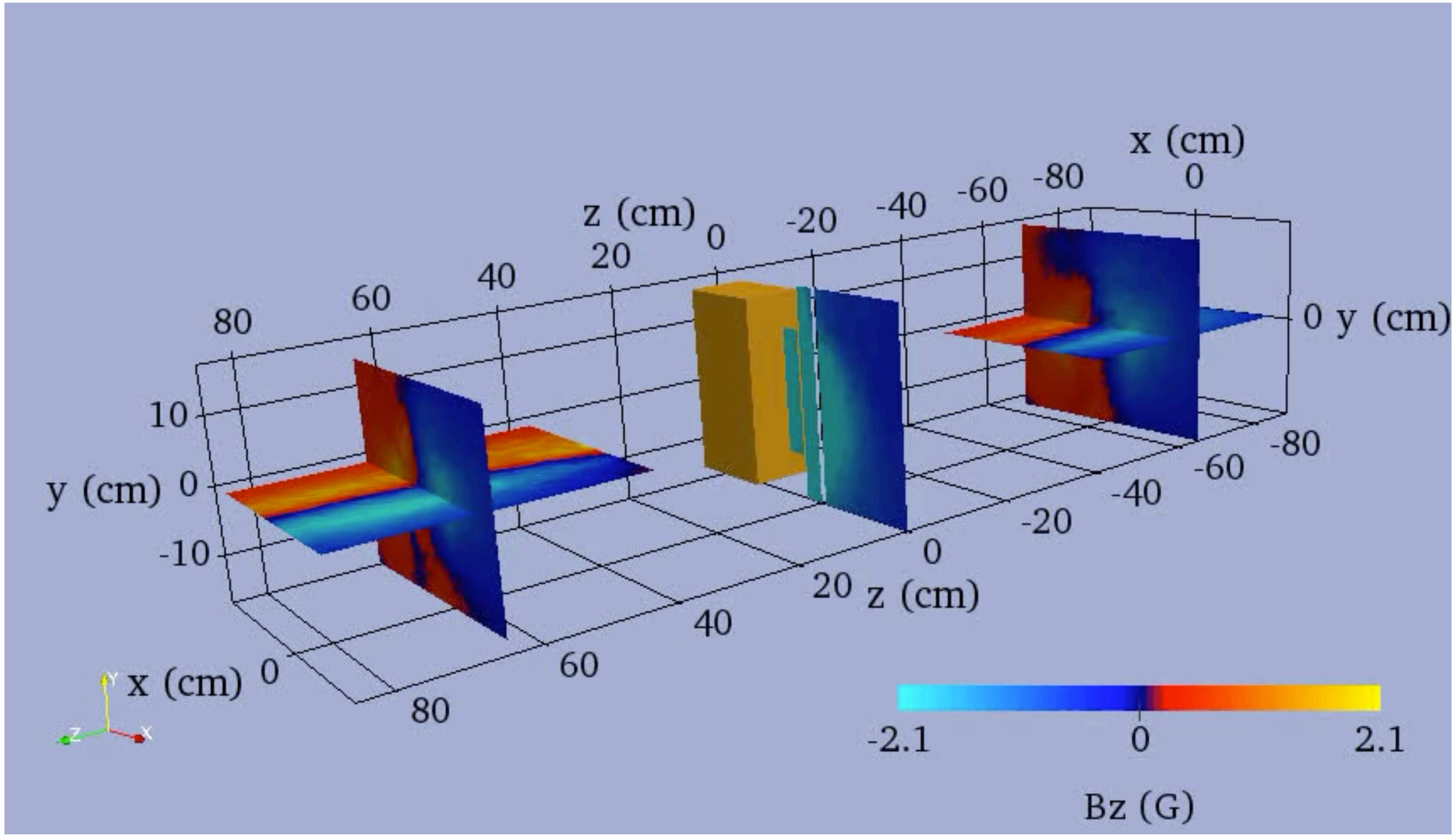


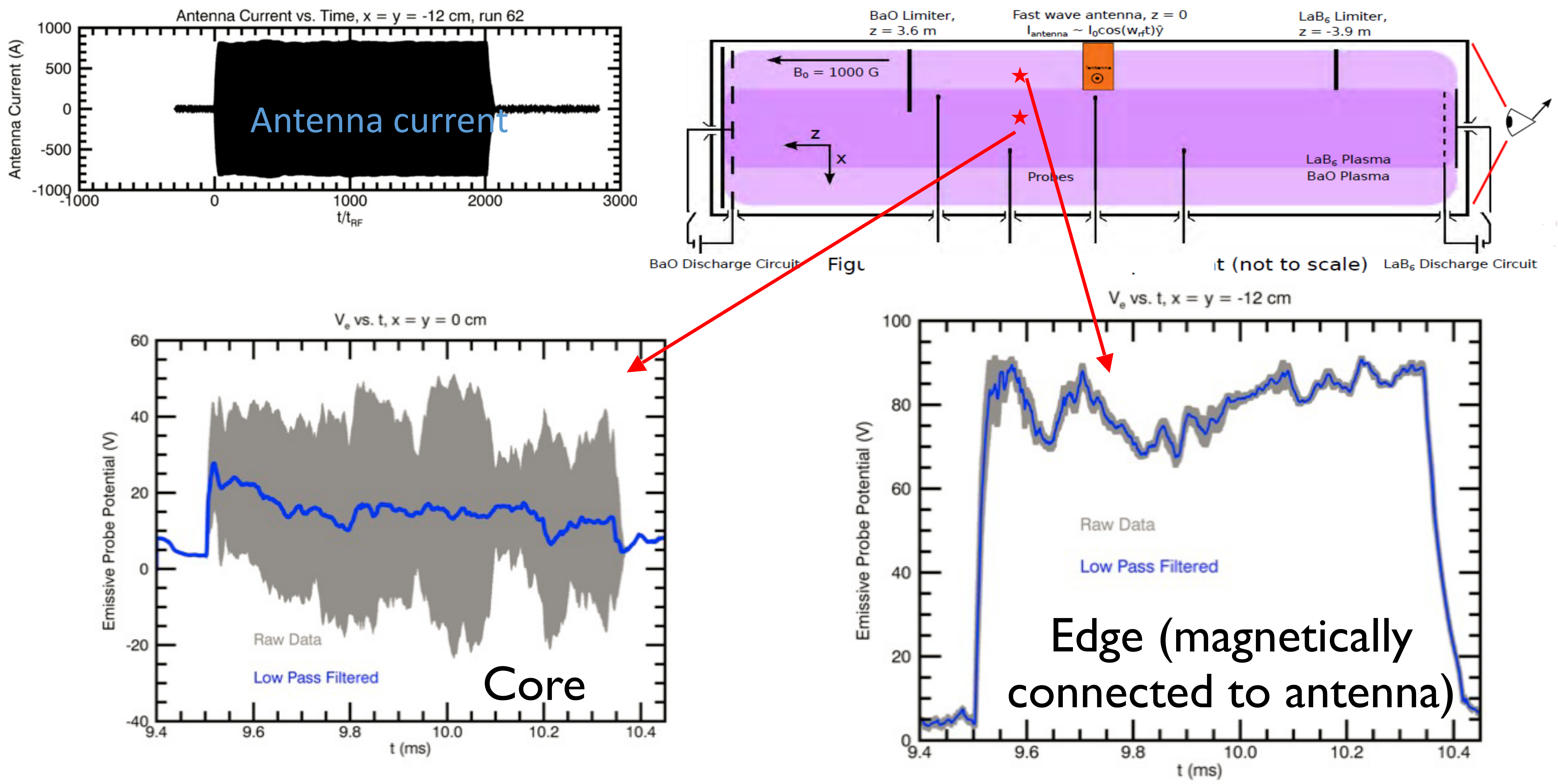

- Single strap fast wave antenna inserted up to edge of high density core (generated by smaller LaB6 cathode)
- Antenna can be tilted to any angle with respect to background field
- High power source: f=1-10 fci, ~200 kW



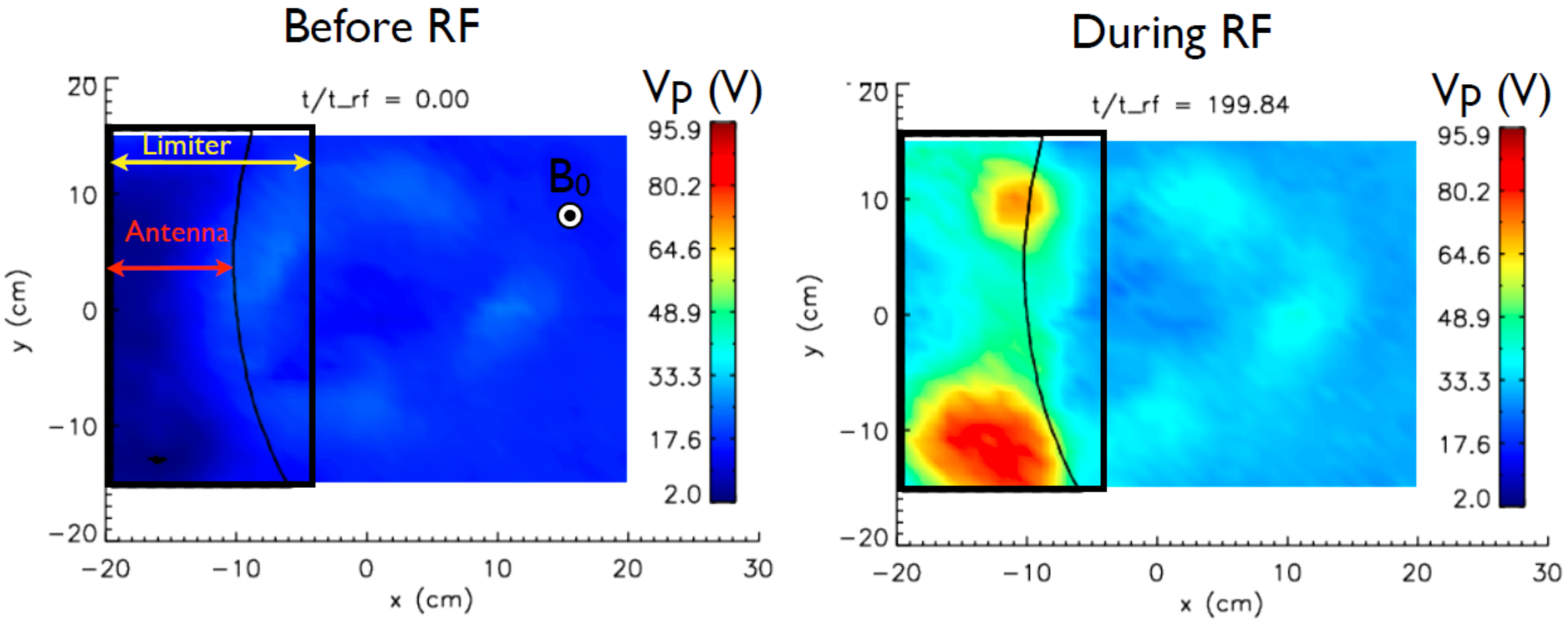
# 3D wave measurements: m=1 fast wave eigenmode excited by single-strap antenna



# Plasma potential measurements show evidence of RF rectification

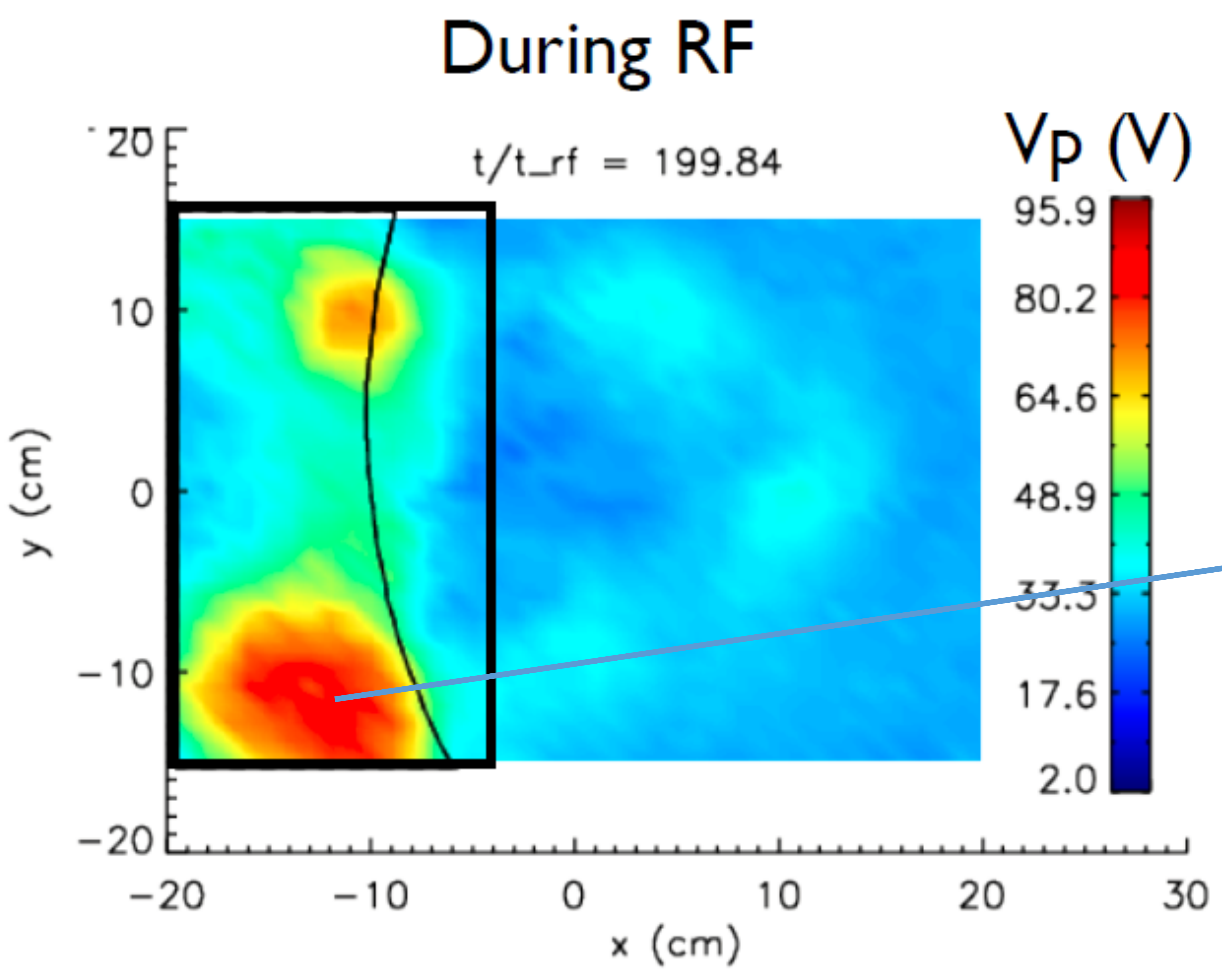


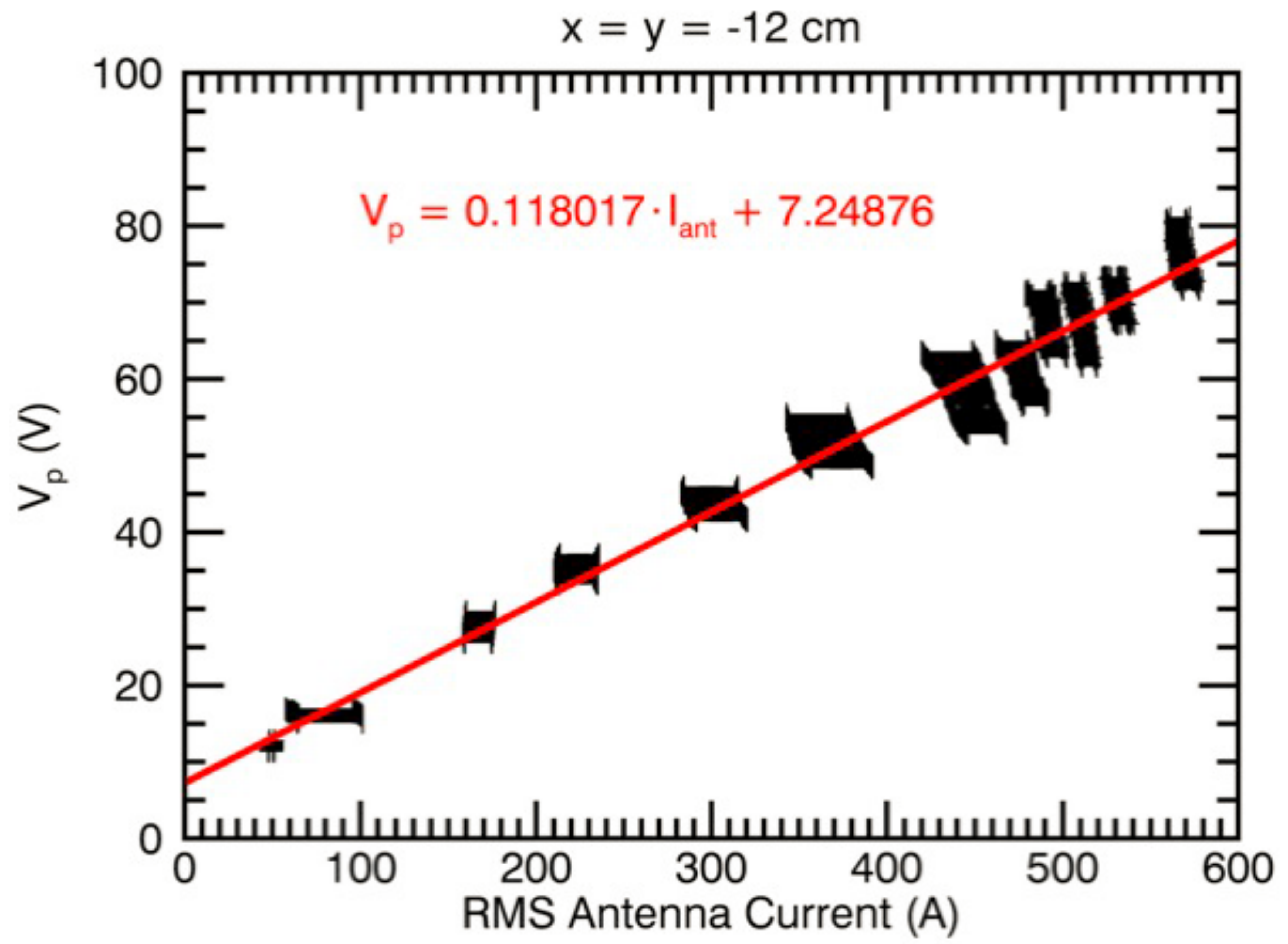
# 2D Potential measurements: potential enhancements localized on antenna structure



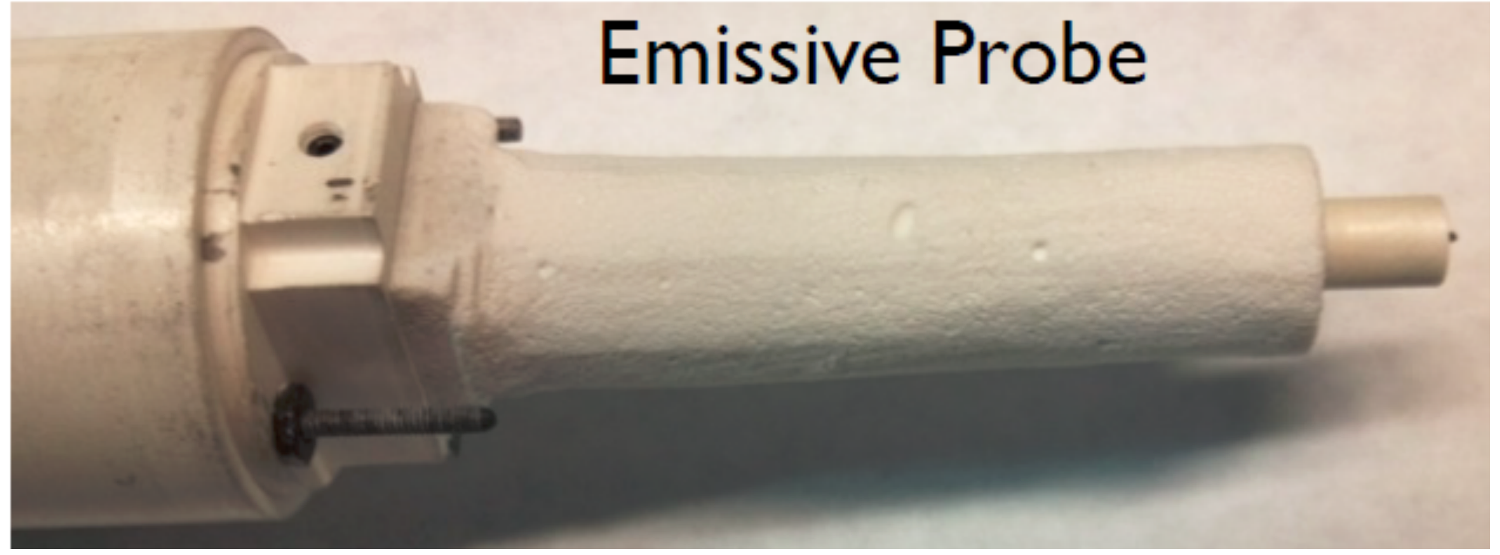

[Martin, et al. PRL 119, 205002 (2017)]

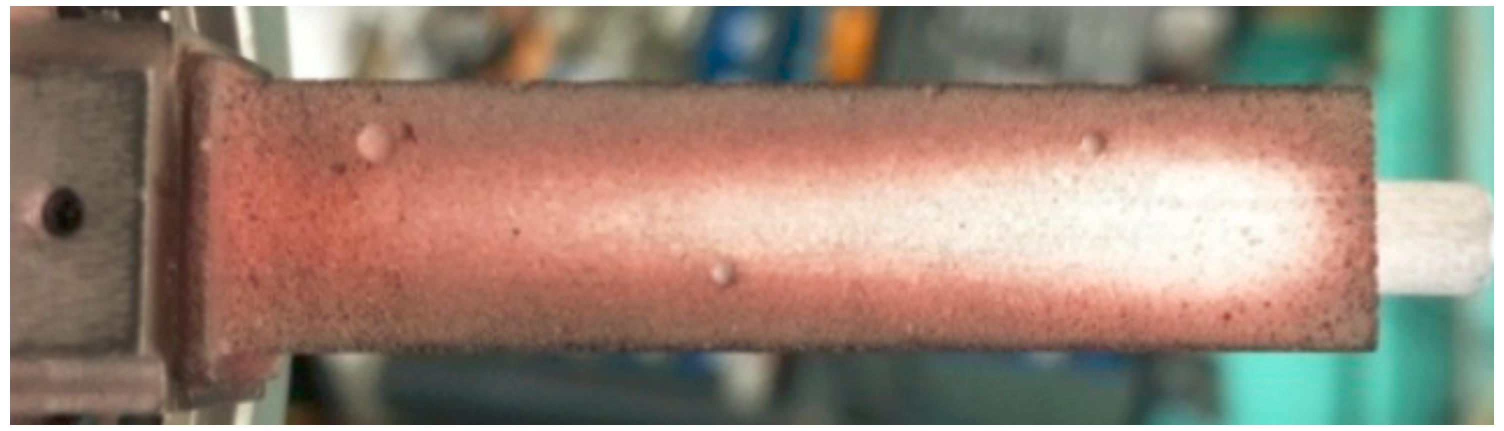
# Potential enhancement scales linearly with antenna current

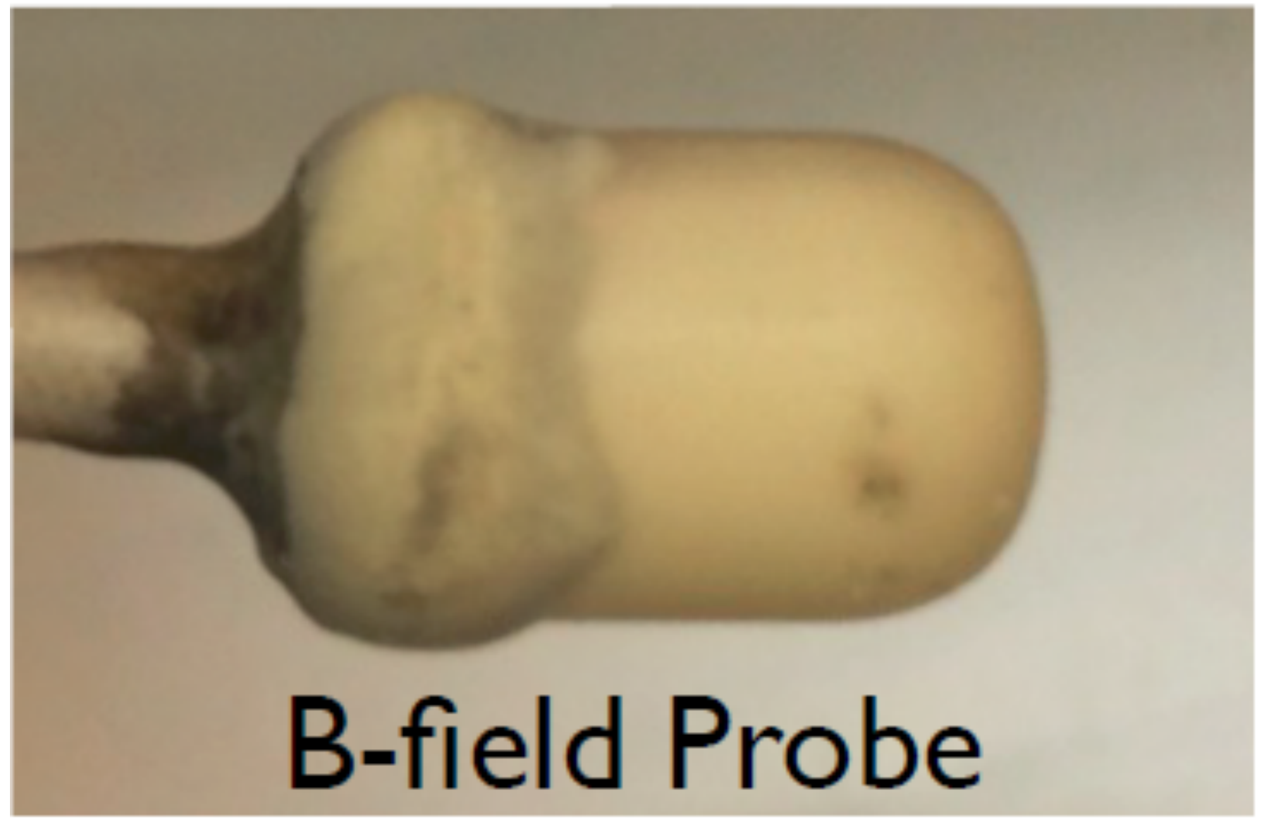


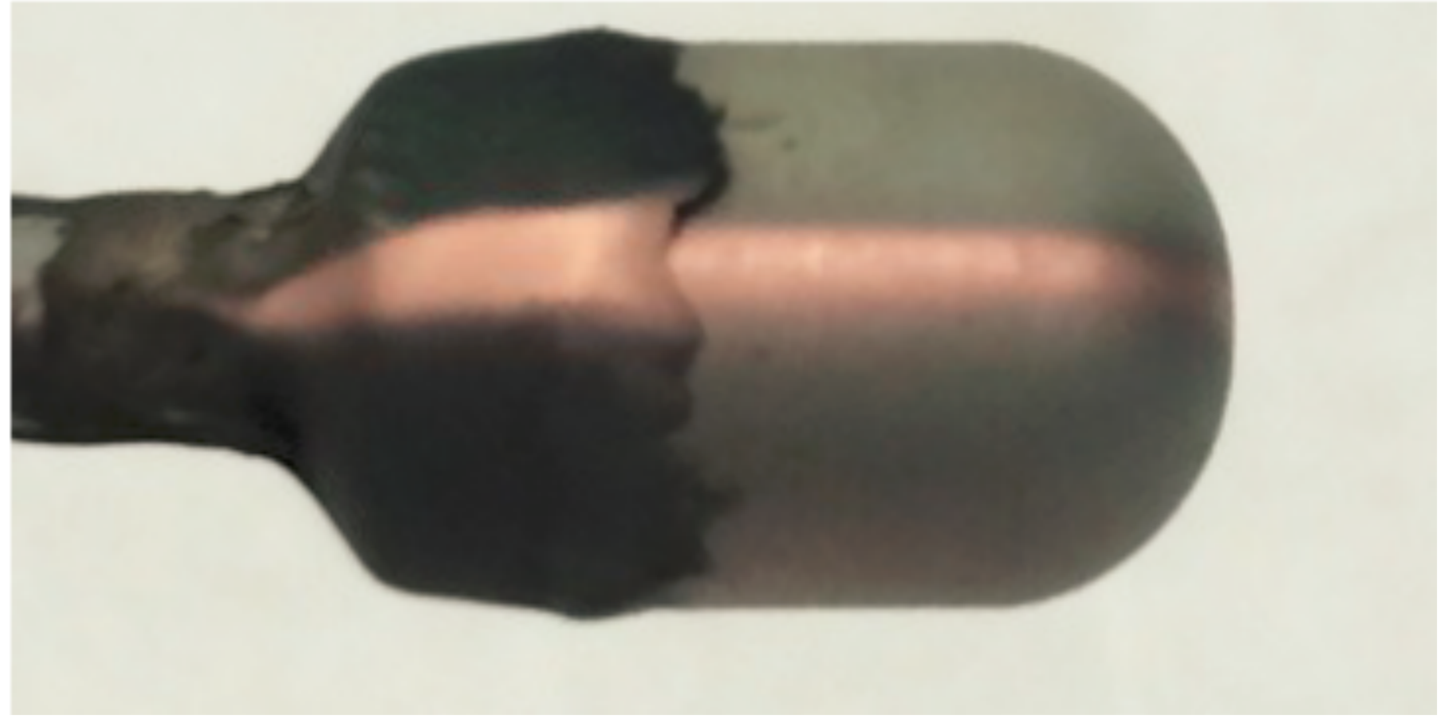



# Sputtering due to RF Rectification



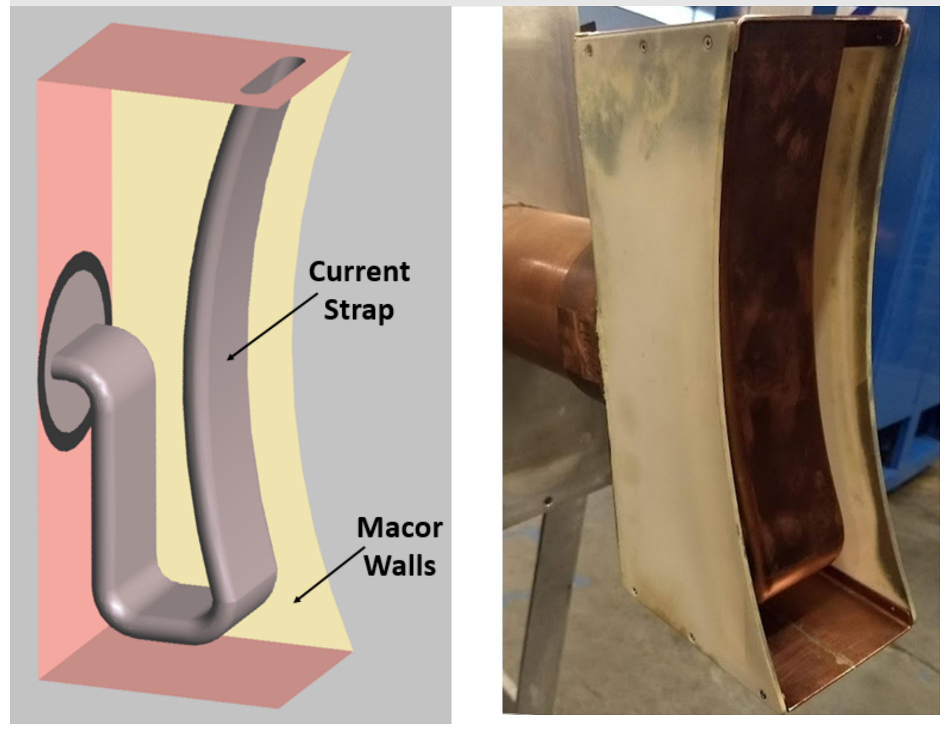


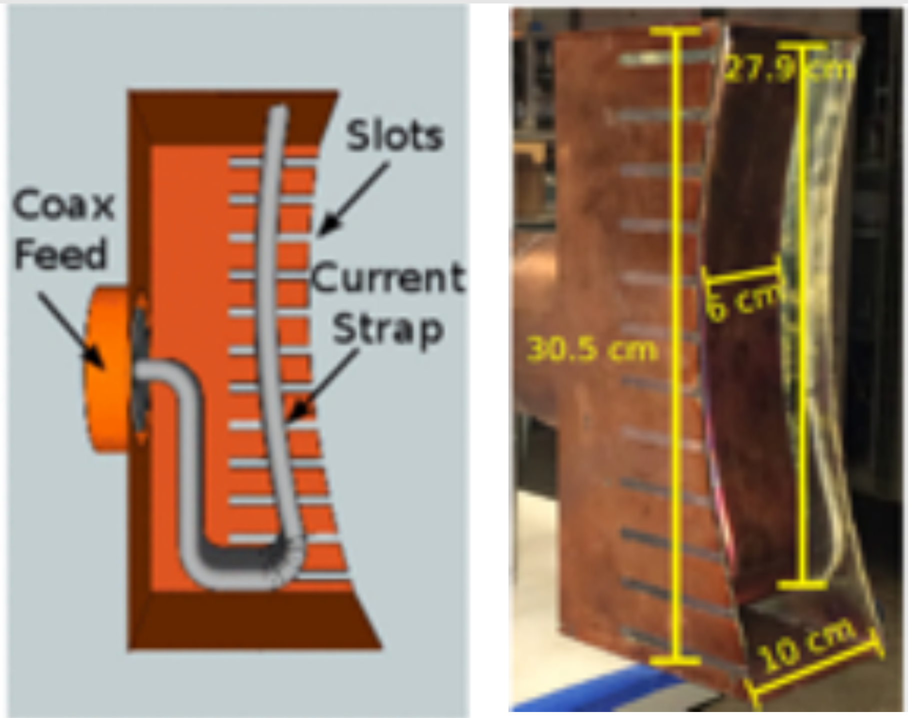
- Probes are coated with copper after experimental run
- Coating likely originates from copper antenna structure

# Mitigating RF sheaths: insulating antenna sidewalls eliminates RF sheath

MACOR ENCLOSURE




COPPER ENCLOSURE

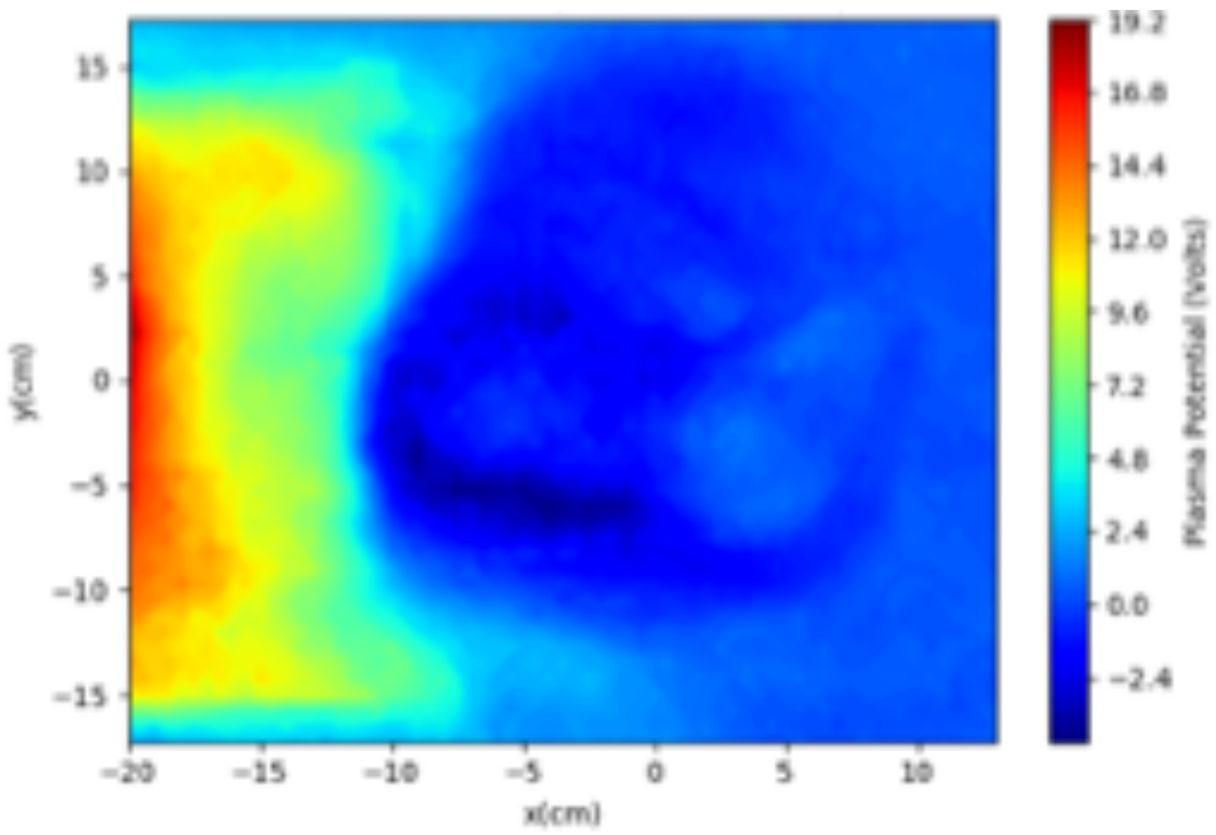


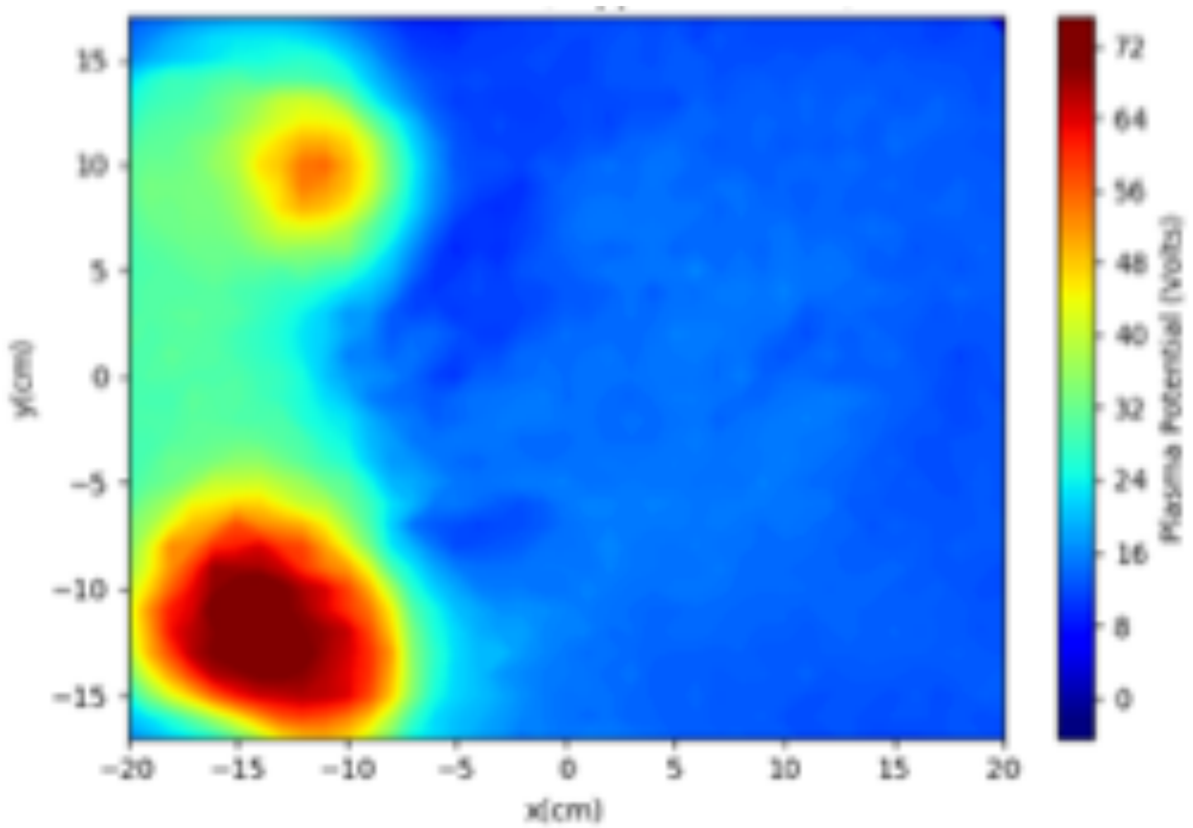

G. Bal, in prep

MACOR ENCLOSURE

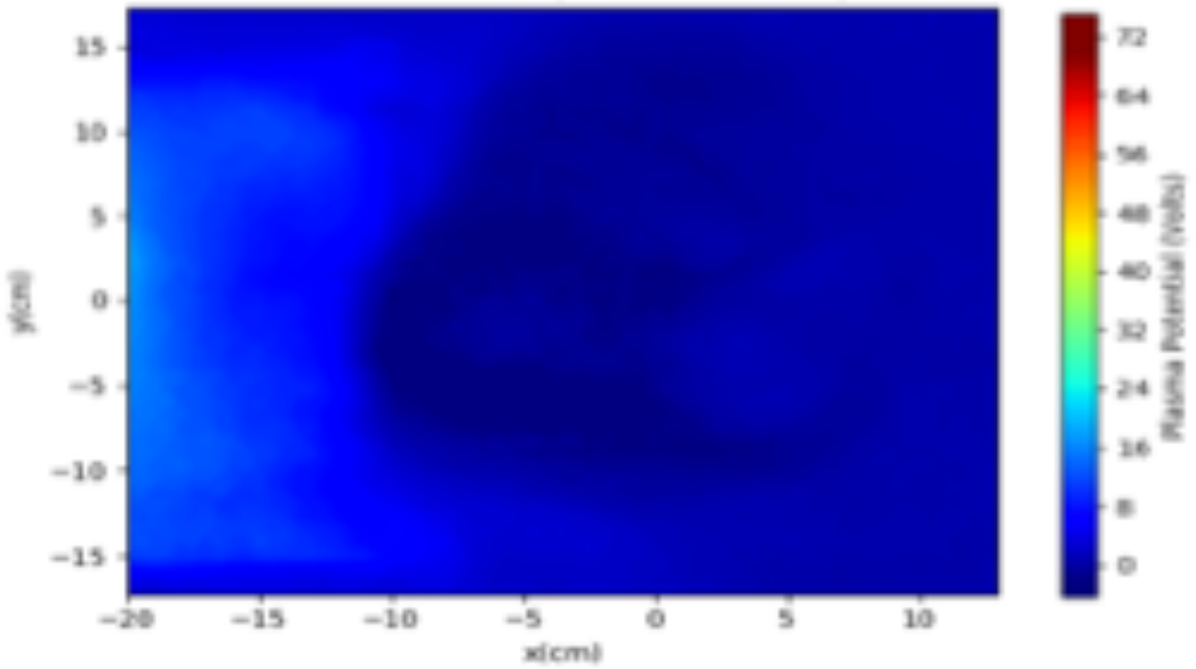
COPPER ENCLOSURE

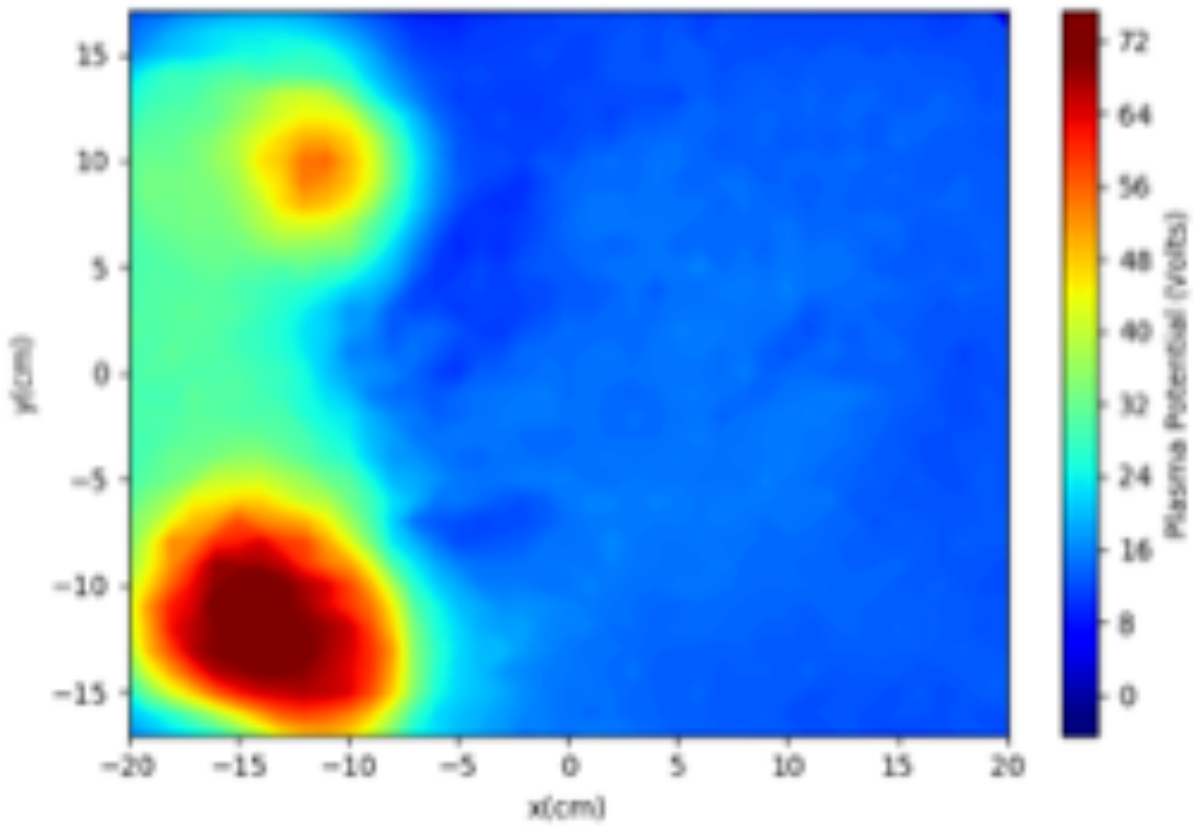
Difference
(Auto Scaled)



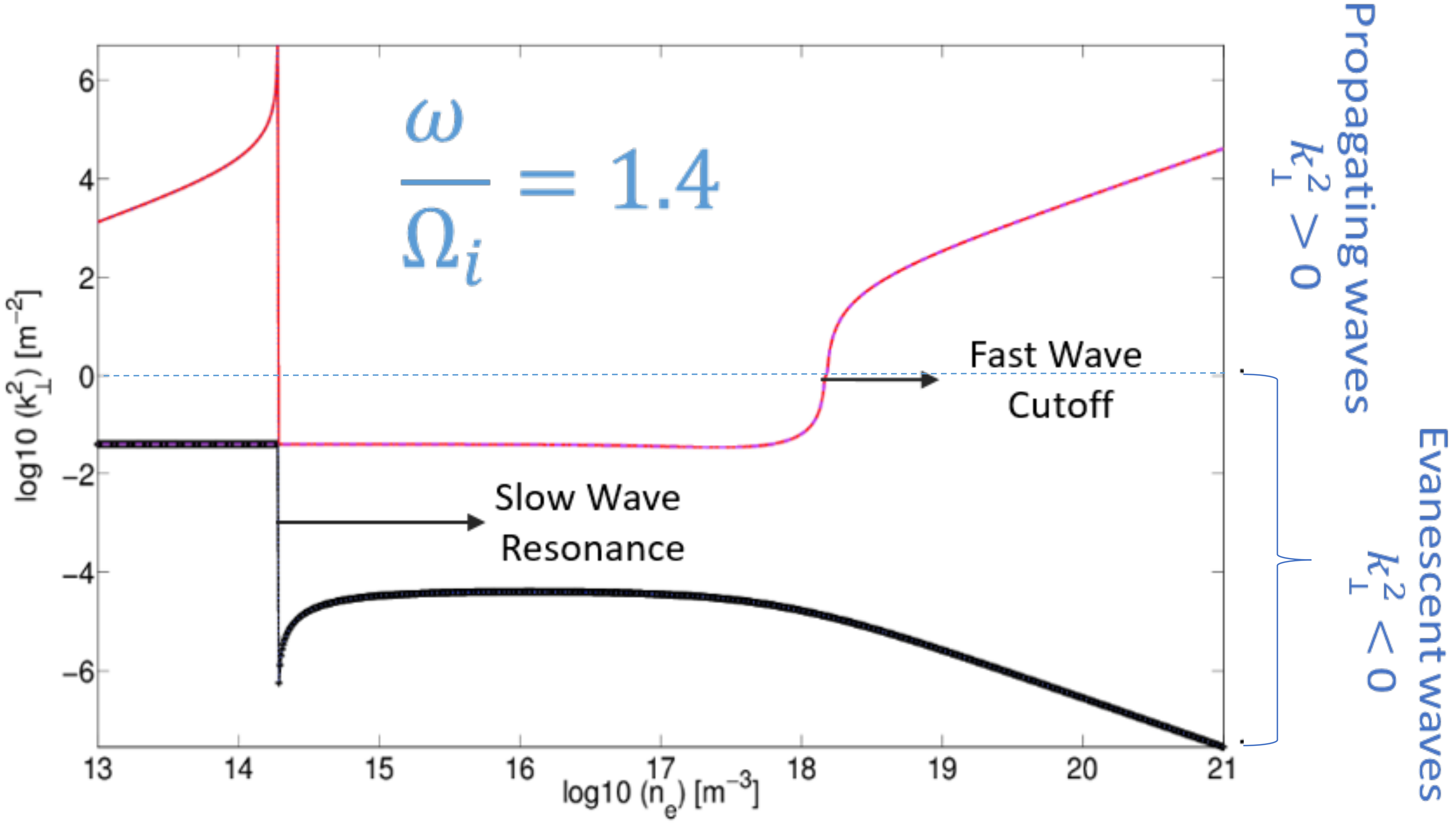

Difference
(Common Color Scale)

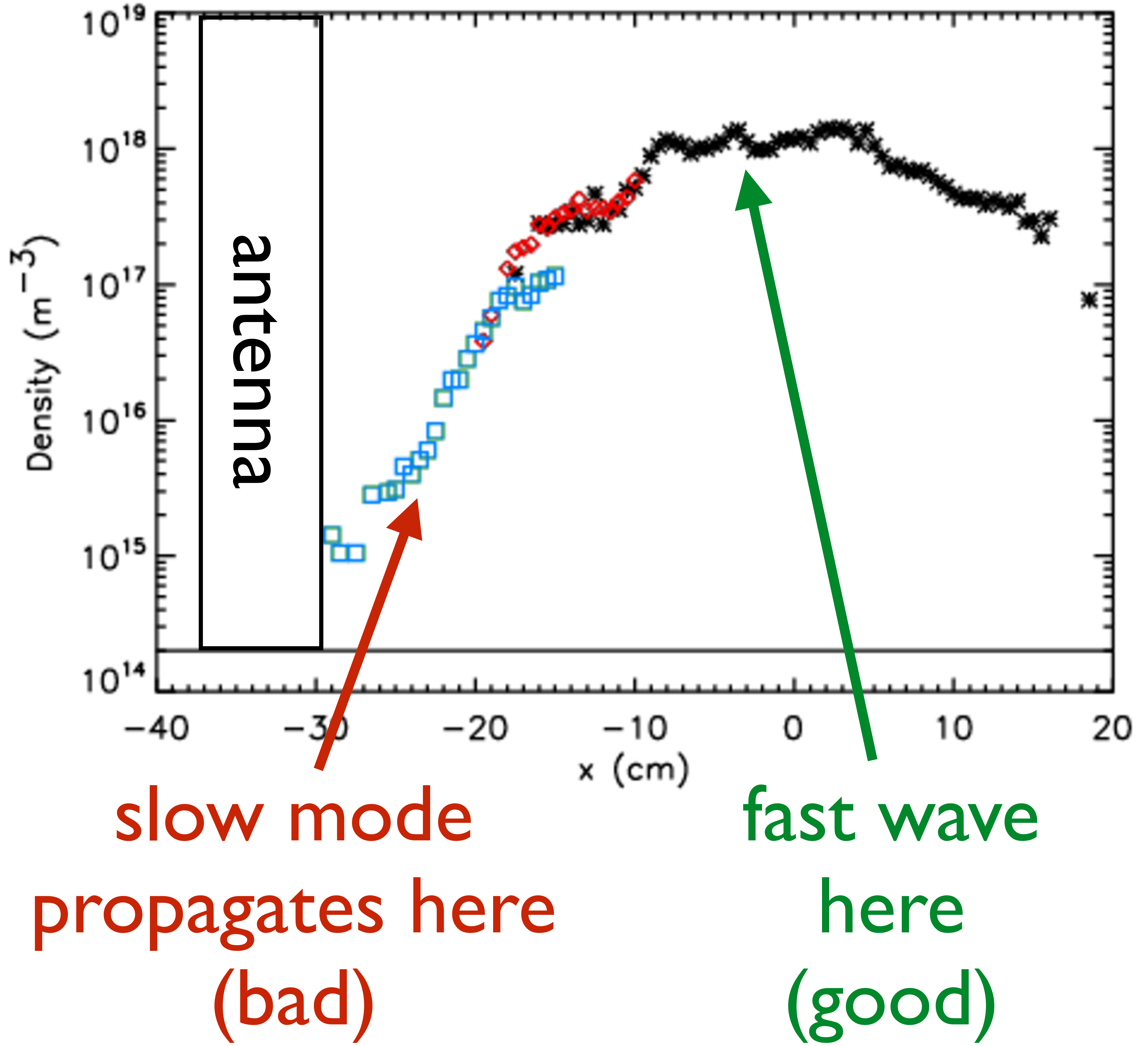


# Parasitic coupling to slow mode in LAPD

If density at antenna is low enough, unwanted coupling to slow mode (LH) is possible, leading to lost power, far-field sheaths, etc.

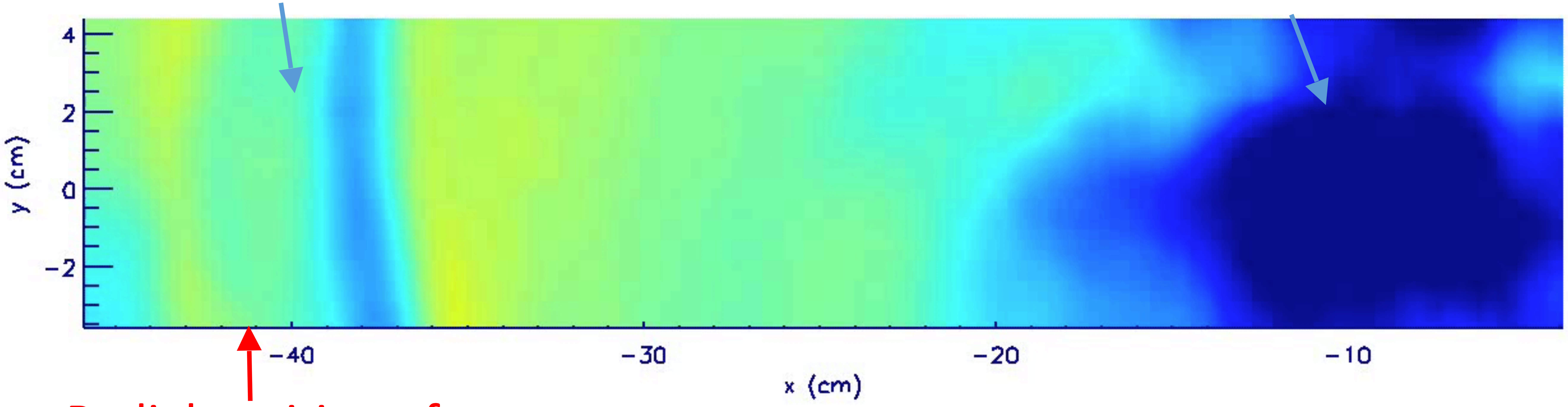


# Parasitic coupling to slow mode observed in low density plasma near antenna

Lower hybrid wave near antenna, backward propagation

Fast wave in high density core plasma, m = 1 mode as before




Radial position of antenna aperture

# Summary

- Basic Plasma Science Facility: US DOE and NSF sponsored user facility for study of fundamental processes in magnetized plasmas. Primary device is Large Plasma Device (LAPD).
- Wide range of studies performed: waves, instabilities, turbulence & transport, shocks, reconnection. Brief highlights of recent experiments will be given, with a longer discussion on Alfvén wave studies, including
  - the first observation of a parametric instability of kinetic Alfvén waves in the laboratory [Dorfman & Carter PRL 2016]
  - High power fast wave excitation in LAPD (ICRF): Measurements of RF rectified sheaths on antenna structure [Martin et al., PRL 2017] and parasitic coupling to slow mode

# 2021 BaPSF Runtime Solicitation

- 50% of LAPD operation time is dedicated to users (other 50% is utilized by BaPSF Group). Typically this is 20 weeks a year for users.
- Runtime is allocated via a runtime proposal solicitation process; TBA. **White Paper Proposals will likely be due Dec 2021**
- ~5 page proposal, provide scientific motivation, experimental resources needed, experimental plan
- External reviews of all proposals, final recommendation made by BaPSF Council and acted on by director
- Details of solicitation, white paper template posted at http://plasma.physics.ucla.edu
- Please feel free to reach out with any questions: tcarter@physics.ucla.edu

(Info on 2019 solicitation)